

ABSTRACT

Title of Document: **CORRELATING Q-FACTOR
MEASUREMENTS TO OTHER
PARAMETERS IN DETERIORATED
CONCRETE**

Cintia Mabel Lijeron,
Master of Science, 2008

Directed By: Professor Amde M. Amde,
Department of Civil and Environmental
Engineering

The impact-echo technique is a nondestructive test used to detect flaws in concrete. Although deterioration can be quantified through the Q-factor, little is known about its relationship to other parameters. This research study explored possible correlations between Q-factors and other parameters including expansion change, weight change, and compression strength in deteriorated concrete. The effect of adding potassium carbonate to accelerate deterioration in concrete was also investigated. Two batches of concrete were used: a control batch with no additional potassium carbonate added and a batch made with a total of 2.06% of potassium carbonate by weight of cement. The specimens were deteriorated through the UMD Modified Duggan Cycle or one of two sets of Freeze-Thaw cycles. The specimens subjected to the heating cycle did not show strong correlations between Q-factors and the other parameters. However, those used in the first set of Freeze-Thaw cycles experienced heavy deterioration and

showed strong correlations between Q-factors and expansion and weight change and those from the second set revealed even stronger correlations.

CORRELATING Q-FACTOR MEASUREMENTS TO OTHER PARAMETERS IN
DETERIORATED CONCRETE

By

Cintia Mabel Lijeron

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2008

Advisory Committee:
Professor Amde M. Amde, Advisor/Chair
Professor Mohamad S. Aggour
Professor Chung C. Fu

© Copyright by
Cintia Mabel Lijeron
2008

Acknowledgements

I would like to thank my advisor Professor Amde M. Amde for his assistance and guidance throughout my graduate years of study. I would also like to thank Dr. Richard Livingston from the Turner-Fairbank Highway Research Center (FHWA) in McLean, Virginia for his assistance during the course of the research, and thank Nicolas McMorris and Jorgomai Ceesay for their help throughout the entire research study. I am also very thankful to the Gates Millennium Scholarship Foundation for their support.

Special thanks to the staff at the Civil and Environmental Engineering Laboratory and the National Ready Mixed Concrete Association Laboratory in College Park, MD for their assistance in sample preparations and technical support.

Lastly, I would also like to thank my husband, Patrick Williams, my parents, and my family for all their support and encouragement.

Table of Contents

Acknowledgements.....	ii
Table of Contents.....	iii
List of Tables.....	v
List of Figures.....	vi
List of Notations.....	x
Chapter 1: Introduction.....	1
1.1 Problem Statement.....	1
1.2 Background.....	1
1.3 Objectives and Scope of Work.....	2
1.4 Outline of Report.....	3
Chapter 2: Literature Review.....	5
2.1 Impact-Echo Method.....	5
2.1.1 Introduction.....	5
2.1.2 Basic Principles and Equations.....	5
2.1.3 The Q-Factor.....	9
2.1.4 Components and Procedure of Impact-Echo Testing.....	11
2.2 Deterioration in Concrete: Delayed Ettringite Formation (DEF) and Alkali-Silica Reactivity (ASR).....	13
2.2.1 Introduction.....	13
2.2.2 Definition and Difference.....	13
2.2.3 Heat Curing.....	14
2.2.4 Previous Research on DEF-related Damage in Concrete.....	15
Chapter 3: Sample Preparation and Deteriorating Methods.....	17
3.1 Introduction.....	17
3.2 Specimen Preparation.....	18
3.2.1 Mix Design and Materials.....	18
3.2.2 Casting Procedure.....	20
3.2.3 Curing Method and Storage Condition.....	23
3.3 Deteriorating Methods.....	24
3.3.1 UMD Modified Duggan Heating Cycle.....	24
3.3.2 Freezing-and-Thawing Cycles.....	25
Chapter 4: Assessment Tests and Procedures.....	29
4.1 Assessment Tests.....	29
4.1.1 Introduction.....	29

4.1.2 Number of Specimens Used.....	30
4.2 Procedures	30
4.2.1 Expansion Test	30
4.2.2 Weight Change Measurements.....	32
4.2.3 Impact-Echo Test	33
4.2.4 Compression Strength Test	36
Chapter 5: Test Results.....	38
5.1 Introduction.....	38
5.2 Expansion Test Results.....	39
5.2.1 Duggan Cycle Batch I and Batch II.....	39
5.2.2 Environmental Chamber Freeze-Thaw Batch I and Batch II.....	41
5.2.3 Cabinet Apparatus Freeze-Thaw Batch I and Batch II.....	43
5.3 Weight Change Measurement Results.....	45
5.3.1 Duggan Cycle Batch I and Batch II.....	45
5.3.2 Environmental Chamber Freeze-Thaw Batch I and Batch II.....	47
5.3.3 Cabinet Apparatus Freeze-Thaw Batch I and Batch II.....	49
5.4 Q-Factor from Impact-Echo Results.....	50
5.4.1 Duggan Cycle Batch I and Batch II.....	50
5.4.2 Environmental Chamber Freeze-Thaw Batch I and Batch II.....	52
5.4.3 Cabinet Apparatus Freeze-Thaw Batch I and Batch II.....	53
5.5 Compression Strength Test Results.....	54
5.5.1 Duggan Cycle Batch I and Batch II.....	54
5.6 Correlation with Q-factors from Impact-Echo Results.....	57
5.6.1 Duggan Cycle Batch I and Batch II.....	57
5.6.1.1 Expansion Correlation.....	57
5.6.1.2 Weight Change Correlation.....	61
5.6.1.3 Compression Strength Correlation.....	63
5.6.2 Environmental Chamber Freeze-Thaw Batch I and Batch II.....	66
5.6.2.1 Expansion Correlation.....	66
5.6.2.2 Weight Change Correlation.....	68
5.6.3 Cabinet Apparatus Freeze-Thaw Batch I and Batch II.....	71
5.6.3.1 Expansion Correlation.....	71
5.6.3.2 Weight Change Correlation.....	73
5.7 Discussion of Results.....	76
Chapter 6: Summary and Conclusions.....	79
6.1 Summary.....	79
6.2 Conclusions.....	80
Appendix.....	83
Bibliography.....	92

List of Tables

Table 2.1: Specific Acoustic Impedance Values for Materials in Concrete.....	7
Table 3.1: Mix Design.....	18
Table 4.1: Schedule of Compression Strength Tests.....	29
Table 4.2: Total Number of Specimens Used in Testing.....	30
Table 5.1: Summary of Compression Strength of Duggan Specimens	56
Table 5.2: Summary of Coefficients of Determination (R^2)	78
Table 6.1: Summary of Measurements of the Duggan Specimens	80
Table 6.2: Summary of Measurements of the first set of Freeze-Thaw Specimens.....	80
Table 6.3: Summary of Measurements of the second set of Freeze-Thaw Specimens.....	80

List of Figures

Figure 2.1: Finite Element Simulation of the Wave Propagation Caused by an Impact.....	6
Figure 2.2: Time Interval between P-wave Arrivals and Frequency of P-wave Arrivals.....	7
Figure 2.3: Frequency Analysis of Impact-Echo Tests.....	8
Figure 2.4: Description of the Q-factor Equation.....	11
Figure 2.5: Commercial Components Used for Impact-Echo Testing.....	12
Figure 3.1: Report of Chemical Analyses of Cement Used.....	20
Figure 3.2: Steel Prism Molds and Non-reusable Cylinder Molds.....	21
Figure 3.3: Steel Gage Studs in Prisms.....	21
Figure 3.4: Motor Oil Spread inside the Prism Molds with a Sponge.....	22
Figure 3.5: Specimens Covered with Aluminum Foil or Lids.....	23
Figure 3.6: Specimens Stored in Limewater.....	24
Figure 3.7: Environmental Chamber Used.....	26
Figure 3.8: Rapid Freeze-Thaw Cabinet apparatus Used.....	27
Figure 3.9: Specimens in the Rapid Freeze-Thaw Cabinet apparatus.....	28
Figure 4.1: Comparator Used for Expansion Tests.....	31
Figure 4.2: Scale Used for Weight Change Measurements.....	32
Figure 4.3: Impact-echo Apparatus.....	34
Figure 4.4: Impact Hammer and Accelerometer of Impact-echo Apparatus.....	34
Figure 4.5: Impact-echo Support Base.....	35
Figure 4.6: Compression Strength Testing Machine Used.....	37
Figure 5.1: Expansion Change Comparison of Duggan Specimens.....	41

Figure 5.2: Expansion Change Comparision of Environmental Chamber Specimens.....	43
Figure 5.3: Expansion Change Comparison of Freeze-Thaw Cabinet Specimens.....	45
Figure 5.4: Weight Change Comparison of Duggan Specimens.....	47
Figure 5.5: Weight Change Comparison of Environmental Chamber Specimens.....	48
Figure 5.6: Weight Change Comparison of Freeze-Thaw Cabinet Specimens.....	50
Figure 5.7: Q-factor Change of Duggan Specimens.....	52
Figure 5.8: Q-factor Change of Environmental Chamber Specimens.....	53
Figure 5.9: Q-factor Change of Freeze-Thaw Cabinet Specimens.....	54
Figure 5.10: Compression Strength of Duggan Specimens with Error Bars	55
Figure 5.11: Q-factor and Expansion Change Correlation of Duggan Specimens.....	58
Figure 5.12: Q-factor and Expansion Change Correlation of Batch I (Duggan).....	60
Figure 5.13: Q-factor and Expansion Change Correlation of Batch II (Duggan).....	60
Figure 5.14: Q-factor and Weight Change Correlation of Duggan Specimens.....	61
Figure 5.15: Q-factor and Weight Change Correlation of Batch I (Duggan).....	62
Figure 5.16: Q-factor and Weight Change Correlation of Batch II (Duggan).....	63
Figure 5.17: Q-factor and Compression Strength Correlation of Duggan Specimens.....	64
Figure 5.18: Q-factor and Compression Strength Correlation of Batch I (Duggan)..	65
Figure 5.19: Q-factor and Compression Strength Correlation of Batch II (Duggan).....	65
Figure 5.20: Q-factor and Expansion Change Correlation of Env. Chamber Specimens.....	66
Figure 5.21: Q-factor and Expansion Change Correlation of Batch I (Env. Chamber).....	67

Figure 5.22: Q-factor and Expansion Change Correlation of Batch II (Env. Chamber).....	68
Figure 5.23: Q-factor and Weight Change Correlation of Env. Chamber Specimens.....	69
Figure 5.24: Q-factor and Weight Change Correlation of Batch I (Env. Chamber).....	70
Figure 5.25: Q-factor and Weight Change Correlation of Batch II (Env. Chamber).....	70
Figure 5.26: Q-factor and Exp. Change Correlation of F-T Cabinet Specimens.....	71
Figure 5.27: Q-factor and Expansion Change Correlation of Batch I (F-T Cabinet).....	72
Figure 5.28: Q-factor and Expansion Change Correlation of Batch II (F-T Cabinet).....	73
Figure 5.29: Q-factor and Weight Change Correlation of F-T Cabinet Specimens.....	74
Figure 5.30: Q-factor and Weight Change Correlation of Batch I (F-T Cabinet).....	75
Figure 5.31: Q-factor and Weight Change Correlation of Batch II (F-T Cabinet).....	75
Figure A.1: Duggan Batch I- Expansion vs. Concrete Age after Duggan Cycle.....	84
Figure A.2: Duggan Batch II- Expansion vs. Concrete Age after Duggan Cycle.....	85
Figure A.3: Environmental Chamber Batch I- Expansion vs. Number of Cycles.....	86
Figure A.4: Environmental Chamber Batch II- Expansion vs. Number of Cycles....	86
Figure A.5: Freeze-Thaw Cabinet Batch I- Expansion vs. Number of Cycles.....	87
Figure A.6: Freeze-Thaw Cabinet Batch II- Expansion vs. Number of Cycles.....	87
Figure A.7: Duggan Batch I- Weight Change vs. Concrete Age after Duggan Cycle.....	88

Figure A.8: Duggan Batch II- Weight Change vs. Concrete Age after Duggan Cycle.....	89
Figure A.9: Environmental Chamber Batch I- Weight Change vs. Number of Cycles.....	90
Figure A.10: Environmental Chamber Batch II-Weight Change vs. Number of Cycles.....	90
Figure A.11: Freeze-Thaw Cabinet Batch I- Weight Change vs. Number of Cycles.....	91
Figure A.12: Freeze-Thaw Cabinet Batch II- Weight Change vs. Number of Cycles.....	91

List of Notations

Batch I	Control batch made with no varying parameters prepared with cement containing 0.56% of potassium carbonate by weight of cement
Batch II	Batch prepared with an added 1.5% of potassium carbonate using cement containing 0.56% of potassium carbonate, thus containing a total of 2.06% of potassium carbonate by weight of cement
Avg. Batch I	Average of specimens from Batch I
Avg. Batch II	Average of specimens from Batch II
B1.2-B1.7	Specimens subjected to the Duggan Cycle or to Freeze-Thaw cycles in the Environmental Chamber from Batch I
B2.1-B2.7	Specimens subjected to the Duggan Cycle or to Freeze-Thaw cycles in the Environmental Chamber from Batch II
B1F.1-B1F.3	Specimens subjected to Freeze-Thaw cycles in the Rapid Freeze-Thaw Cabinet apparatus from Batch I
B2F.1-B2F.3	Specimens subjected to Freeze-Thaw cycles in the Rapid Freeze-Thaw Cabinet apparatus from Batch II

Chapter 1: Introduction

1.1 Problem Statement

Nondestructive tests such as the impact-echo test have shown promise in accurately detecting deterioration in concrete. In this test, deterioration in concrete can be quantified by the Q-factor value. However, little is known about the relationship of this value to other parameters such as expansion change, weight change and compression strength. Understanding how this quantity relates to these and other parameters could help lead to a better assessment of deterioration found in concrete. The purpose of this research study was to observe if a correlation between the Q-factor obtained from deteriorated specimens and other parameters existed. The effect of adding potassium carbonate to accelerate deterioration was also investigated. The specimens consisted of concrete prisms and cylinders made up of two batches which were tested regularly. One batch was used as the control batch, while the other one contained additional potassium carbonate. The addition of potassium carbonate was used to accelerate concrete deterioration through the formation of delayed ettringite as proven by previous research. The data obtained from the specimens subjected to the Duggan Cycle was gathered for a period of approximately five months and the data from the specimens subjected to Freeze-Thaw cycles was gathered until the Q-factors could no longer be obtained.

1.2 Background

This research study further explored results obtained from previous research carried out at the University of Maryland College Park which dealt with finding an

improved impact-echo method for the quantification of damage in concrete. One of the purposes of the previous research was to correlate the Q-factor with other parameters such as expansion change (McMorris, Amde, Cessay, Ramadan, and Livingston, 2007). Two batches of 3" x 3" x 11.5" prism specimens were created for that study. One batch served as the control batch with no additional potassium carbonate added, and the second batch was made with 1.5% potassium carbonate (anhydrous granular reagent grade K_2CO_3) by weight of cement. The purpose of the added potassium carbonate was to increase the alkali content of the concrete in hopes to accelerate deterioration by ettringite formation. The specimens were steam cured at a temperature of 85°C for four hours and stored in three different storing conditions: isothermal water bath with the PH maintained at 12.5, moist air chamber with a RH maintained at 97%, and plain water. After six days of storage the specimens were subjected to the UMD Modified Duggan Test to accelerate deterioration by delayed ettringite formation. This previous study concluded that the rate of expansion of the concrete prisms was increased by the addition of potassium, the Q-factor values obtained corroborated by the expansion results, and that spectral indicators also corroborated with the Q-factor values. Although the results revealed a possible correlation between Q-factors and expansion, they were based on very limited data and a pattern was not clearly obvious.

1.3 Objectives and Scope of Work

The goal of this research study was to find correlations between Q-factors and expansion, weight change, and compression strength from specimens that were subjected to two different DEF accelerating processes: the UMD Modified Duggan

Cycle and Freeze-Thaw cycles. These two tests are known to accelerate deterioration and damage in concrete, which was important to do in a short amount of time in order to observe how the Q-factors changed over time. The objectives of this study are summarized in the following list:

1. Literature review to investigate the Impact-Echo testing method, understand what the Q-factor, resonant frequency, and resonant frequency shift represent;
2. Prepare a concrete mix design, establish a curing method, and decide on a storage method to use;
3. Prepare procedures and methods to accelerate damage and ettringite growth particularly: Duggan Cycle and Freeze-Thaw Testing; and
4. Perform the following tests to gather and analyze data: expansion measurements, weight change measurements, impact-echo testing and compression tests.

1.4 Outline of Report

The report is divided into six chapters. Chapter 2 consists of a literature review of the impact-echo method, its components, what the Q-factor represents and how it is obtained. It also includes a section on concrete deterioration, specifically the type of deterioration expected to be found in the concrete specimens of this study: delayed ettringite formation (DEF) and alkali-silica reaction (ASR). Chapter 3 explains the preparation of the specimens and the methods used to deteriorate them and initiate ettringite growth. The preparation information includes the mix designs, casting and curing method, and storing conditions used. The deteriorating methods discussed in this chapter include the UMD Modified Duggan Cycle and Freeze-Thaw

cycles. Chapter 4 summarizes the tests carried out to assess the deterioration in the specimens, and the procedure of these tests. Finally, Chapter 5 and 6 present the results found, conclusions, and recommendations based on the results.

Chapter 2: Literature Review

2.1 Impact-Echo Method

2.1.1 Introduction

The impact-echo method is a nondestructive technique used to evaluate flaws in concrete. It was developed at the U.S. National Institute of Standards and Technology and at Cornell University during the mid-1980s. This testing method is used to calculate the thickness of a member and to locate cracks, delaminations, and voids by detecting the presence of interfaces between materials with different mechanical properties. This technique is based on analyzing the responding propagation of waves resulting from a mechanical impact on the test object. Some of the factors that affect the detection of a flaw include the type of flaw and its orientation, its depth, and the contact time of the impact. According to Sansalone and Carino (1988) and Lin and Sansalone (1996), this method can detect planar concrete-air interface parallel to the test surface, such as delaminations and voids most accurately.

2.1.2 Basic Principle and Equations

There are three different waves that propagate through the test object from an impact, a P-wave, an S-wave, and an R-wave. The P-wave, associated with normal stress, and the S-wave, associated with shear stress, both travel spherically through the object where as the R-wave travels away from the impact but along the surface of the object. Figure 2.1 illustrates a finite element simulation of the wave propagation caused by an impact on a plate (Sansalone and Carino, 1986). The speeds of these

waves can be calculated by using the mechanical properties of the material which include: the Young's modulus of elasticity, Poisson's ratio, density, and shear modulus of elasticity.

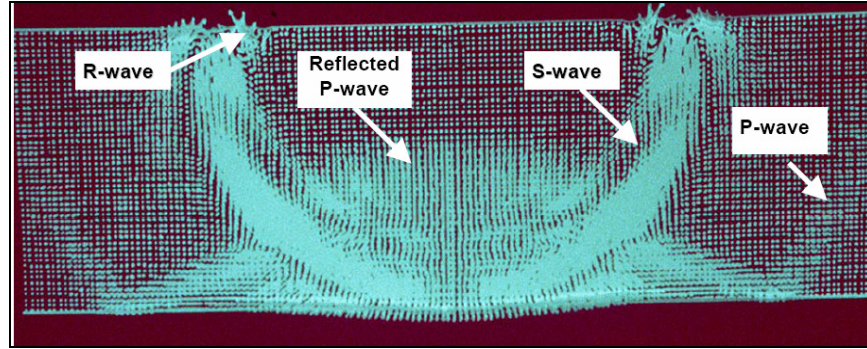


Figure 2.1: Finite Element Simulation of the Wave Propagation Caused by an Impact

After an impact, P-waves and S-waves are reflected by either internal defects such as voids and cracks or external boundaries. The reflection's amplitude of a wave that encounters a different material depends on the angle of incidence with 90° being the maximum, which is referred to as normal incidence. At normal incidence, the reflection coefficient, R , becomes a function of the specific acoustic impedance of both materials encountered (Krautkramer and Krautkramer, 1990) as shown by the equation:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

$Z_2 =$ specific acoustic impedance of material 2

$Z_1 =$ specific acoustic impedance of material 1

Using the approximate specific acoustic impedance values for common materials found in concrete by Sansalone and Carino (1991), shown in Table 2.1, it can be seen that an interface with air would nearly result in total reflection of the waves.

Table 2.1: Specific Acoustic Impedance Values for Materials in Concrete

Material	Specific acoustic impedance, $\text{kg}/(\text{m}^2 \text{ s})$
Air	0.4
Water	0.5×10^6
Soil	$0.3 \text{ to } 4 \times 10^6$
Concrete	$7 \text{ to } 10 \times 10^6$
Steel	47×10^6

Each time the reflected waves (P-waves and S-waves) travel back to the surface they produce displacements which are then measured by a receiving transducer located near the point of impact. Figure 2.2 shows that in the time domain the time interval, Δt , between P-wave arrivals at the test surface equals to the travel distance (twice the depth of the reflecting interface, $2T$) divided by the speed of the wave, C_{pp} . The frequency, f , of the P-wave arrival is the inverse of this relationship (Carino, 2001).

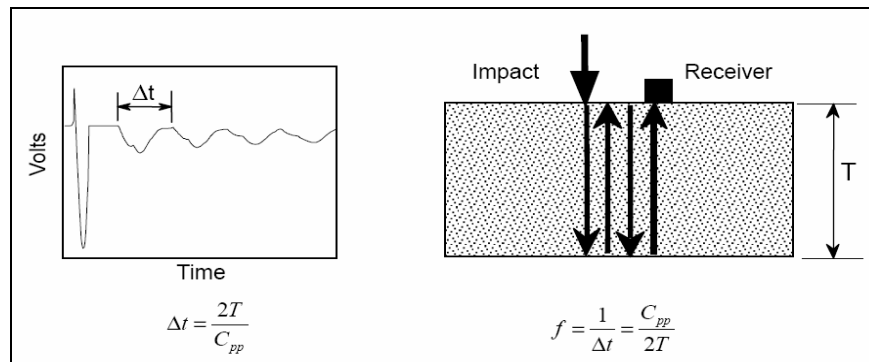


Figure 2.2: Time Interval between P-wave Arrivals and Frequency of P-wave Arrivals

To analyze the waveforms obtained from an impact-echo test, the waveforms are transformed from time domain into frequency domain using the Fast Fourier Transform technique. The result of this transformation is an amplitude spectrum which shows the various frequencies included in the waveform with the peak frequency representing the thickness of the reflecting source (Sansalone and Carino, 1986). The frequency analysis principle is summarized below in Figure 2.3.

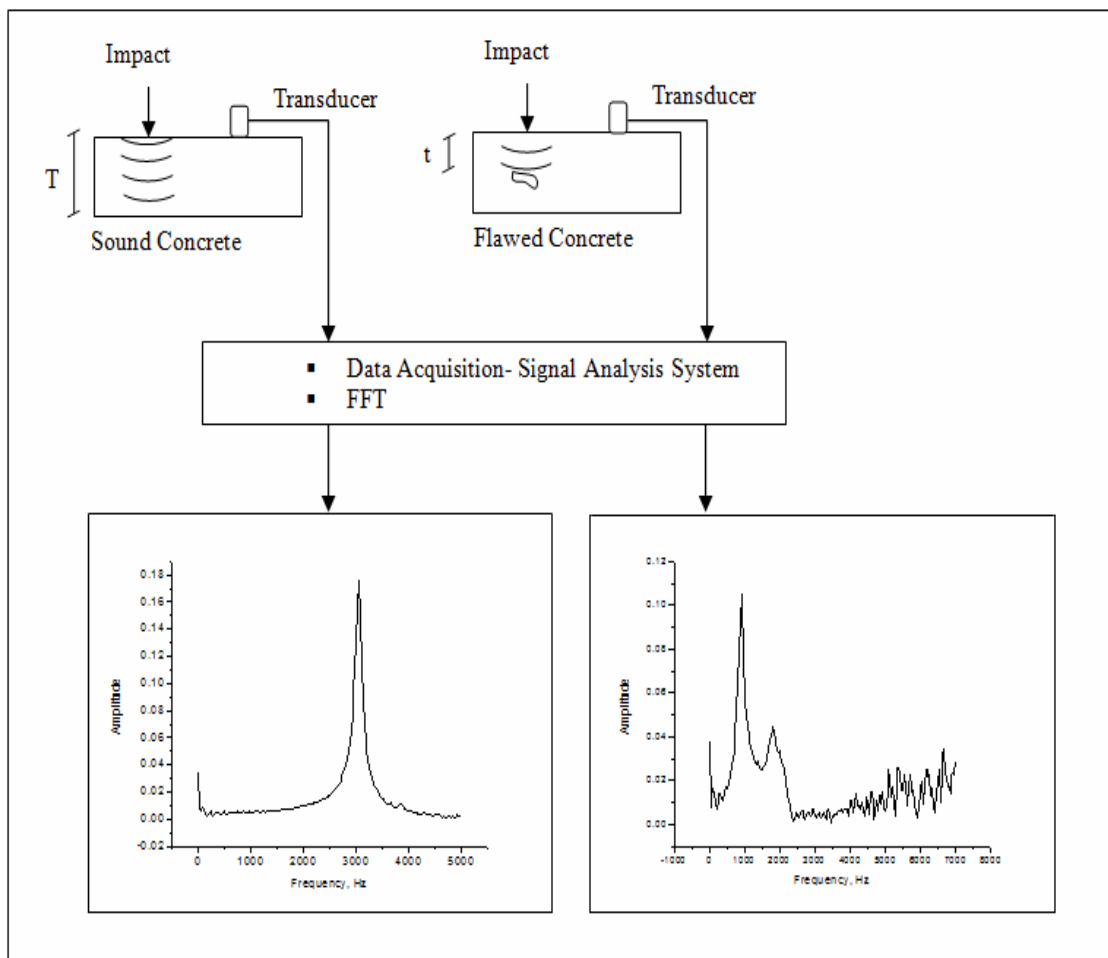


Figure 2.3: Frequency Analysis of Impact-Echo Tests

To calculate the depth of a flaw, t , in a concrete specimen as shown in Figure 2.3, the overall thickness of the specimen, T , or the thickness of a similar size specimen must be known. With this information, the P-wave speed (C_{pp}) can then be calculated using the peak frequency from the frequency domain of the sound concrete specimen and the equation below by solving for C_{pp} . Once the P-wave speed is known, the depth of the defect, t , can be found by using the peak frequency of the flawed concrete specimen and the equation below but this time interpreting the value of “ T ” as “ t ” since the peak frequency of the flawed specimen is used.

$$T = \frac{C_{pp}}{2f}$$

T = Overall thickness of specimen

C_{pp} = P-wave speed

f = Peak frequency from the frequency domain

2.1.3 The Q-factor

The quality factor, or quantity Q , of a forced vibration is a measure of the sharpness of resonance and it also can be interpreted as the inverse of the measure of internal damping. A decrease in Q -factor is thought to be an indication of micro-cracking in concrete according to AASHTO Designation TP18. Sansalone et al (1997) have shown that a small flaw will shift the thickness frequency response to a lower value, even when the frequency peak does not change. Additionally, El-Korchi, Gress, Baldwin, and Bishop (1989) stated that the Q -factor is more sensitive to changes within the structure even when changes in the natural frequency are not

observed. It was also concluded by El-Korchi et al (1989) that a decrease in the Q-factor would indicate an increase in structural deterioration.

The Q-factor value is obtained from the data after it has been converted to a frequency response using a Fast Fourier Transform (FFT) by fitting a standard frequency response curve to the measured data. Previous research has found that a Lorentzian curve is a good fit for this type of data (McMorris et al, 2007). The value is calculated by using the fundamental frequency, f_n , and the two frequencies on both sides of the resonance at 0.707 times the amplitude, f_1 and f_2 , as shown in the equation below. The Q-factor is independent of the dimensions of the structure. Figure 2.4 describes the parameters used in the Q-factor equation below (Thomson, 1981):

$$Q = \frac{f_n}{f_2 - f_1}$$

f_n = Fundamental frequency

f_1, f_2 = Frequencies at both sides of the resonance at 0.707 times the amplitude

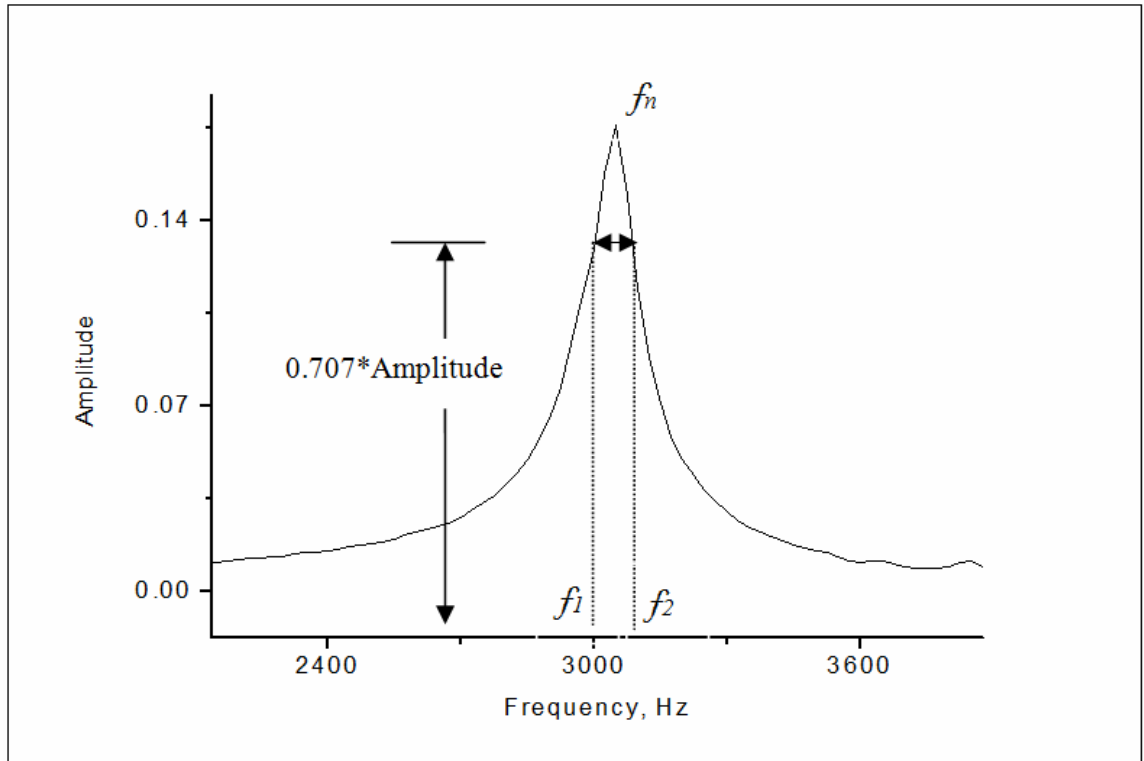


Figure 2.4: Description of the Q-factor Equation

2.1.4 Components and Procedure of Impact-Echo Testing

The impact-echo test method requires three components: a mechanical impactor used to produce short-duration impacts, a receiver to measure the surface response to the impact, and a data acquisition-signal analysis system, i.e. computer, to process and store the waveforms produced. The impactor used in the field usually consists of different diameter steel balls that are attached to a spring-steel rod. The selection of the appropriate diameter size steel ball plays an important part in detecting different sizes of flaws based on the impact duration the ball produces. The transducer measures the surface motion caused by the impact receiver and is often attached to the concrete surface with a grease-like material. Sansalone and Streett

(1997) also suggested that the distance between the placing of the impact point and transducer is crucial and recommend a spacing of less than 40% of the depth.

There are many portable commercial impact-echo products available for field use. Figure 2.5 below shows a commercial product manufactured by Impact-Echo Instruments LLC and currently used for impact-echo testing in the field.



Figure 2.5: Commercial Components Used for Impact-Echo Testing

The procedure used in the field consists of producing a short-duration mechanical impact by tapping a small steel sphere against a concrete or masonry surface. The impact produces low-frequency stress waves that travel through the structure and are reflected by flaws and/or the external surface. The wavelengths of these stress waves are typically longer than the scale of natural inhomogeneous regions in concrete resulting in propagation through the concrete as though it were a homogeneous elastic medium. The resulting surface displacements are recorded by a

transducer and the resulting voltage-time signal is sent to the data acquisition system where it is digitized and transferred to the memory of a computer. In the computer, the voltage-time signal is transformed by FFT into a spectrum of amplitude versus frequency; both the waveform and spectrum are plotted on the computer screen. The dominant frequencies appear as peaks and can then be classified as associated with multiple reflections of stress waves within the structure or with flexural vibrations in thin or delaminated layers.

2.2 Deterioration in Concrete: Delayed Ettringite Formation (DEF) and Alkali-Silica Reactivity (ASR)

2.2.1 Introduction

Delayed ettringite formation and alkali-silica reaction are known to be destructive to concrete. Alkali-silica reaction damaged concrete can be treated. However, delayed ettringite formation can damage concrete further by widening cracks which can lead to failure (Hime and Marusin, 1999).

2.2.2 Definition and Difference

Ettringite forms in concrete after a few months or years of placement in a moist environment and it is known to be destructive. It forms due to a reaction between gypsum and calcium aluminate (Day, 1992). The primary ettringite growth does not cause damage to the concrete, however its growth later on caused by environmental conditions or chemical reactions becomes known as delayed ettringite formation and can be destructive. The term “delayed ettringite formation” has been controversial and was probably coined by Heinz and Ludwig in 1989. Other terms

that have been used include: secondary ettringite formation, late ettringite formation, and even internal sulfate attack. Alkali silica reaction or ASR is a reaction between alkalis found in cement and reactive silica usually found in aggregates. This reaction forms a gel which increases in volume in moist environments that applies pressure on the concrete causing it to expand and crack. Alkali-silica reaction often appears as map cracking on concrete surfaces. It is important to distinguish between DEF and ASR since misinterpretations between them are believed to frequently occur because both produce similar appearances. ASR is usually recognized for the formation of a gel and rims around aggregate particles, however in DEF microscopic ettringite crystals could appear as a “gel” as well.

Although alkali-silica reaction has been researched far more extensively than delayed ettringite formation, it is believed that DEF could have been misinterpreted as ASR in the past (Hime and Marusin, 1999). Other researchers believe DEF is a consequence of ASR because it was found in distressed concrete railway ties produced in Germany (Lawrence, 1993) and Finland (Tepponen, 1987) among other countries. However, Hime and Marusin (1999) argue that it is more likely that either DEF in the ties promoted ASR or that the complete reaction of alkali sulfate to produce ettringite led to unusual reactivity of the released alkalies. Researchers agree that more research is needed on DEF to understand its connection to ASR.

2.2.3 Heat Curing

In 1992, Day conducted a literature analysis of the effect of secondary ettringite formation on the durability of concrete. Day concluded that secondary

ettringite formation can lead to significant deterioration in heat-treated concrete by producing expansion and cracking. The study stated that an early heat treatment at temperatures above 70° C can result in sulphates being bound in an unusual form which could be released back into a solution later, providing a supply of sulphate ions for secondary ettringite formation. Conversely, other researchers have found the identical development of ettringite in non-steam cured concrete (Mielenz, Marusin, Hime, and Jugovic, 1995).

Previous research done at the University of Maryland College Park has also shown that heat curing can accelerate damage in concrete. Azzam (2002) concluded that the amount of expansion of steam-cured concrete prisms were higher than those which were water-cured for the same level of potassium content. Additionally, it was concluded that there is reduction in compressive strength due to steam curing as it was found that the compressive strength of steam-cured concrete was 2376 psi at day one and 2077 psi a year later.

2.2.4 Previous Research on DEF-related Damage in Concrete

In 2007, Ceesay conducted research at the University of Maryland College Park on the characterization of damage in mortar and concrete specimens due to the formation of delayed ettringite (DEF). The concrete specimens in this study were subjected to the Duggan Heat Cycle and a specific Freeze-Thaw Cycle to initiate microcracks in a short amount of time. An objective of the study was to investigate the DEF-related damage in concrete based on the effect of potassium content and different exposure conditions. The specimens used for the Duggan Heat Cycle were

steam-cured while the specimens used for the Freeze-Thaw Cycle were room temperature cured. The specimens used in that study consisted of a control batch and a batch with 1.5% of potassium per weight of cement. The potassium in the cement was taken into consideration when the 1.5% of potassium per weight of cement was calculated. Different storing conditions were used which included limewater, plain water, and field conditions among others. Ceesay (2007) concluded ettringite was found after 40 days of the Duggan Heat Cycle in all of the specimens from the control batch. As for the specimens with 1.5% potassium per weight of cement, ettringite was found after 40 days only in those stored in limewater. Ettringite was found in both batches subjected to the Freeze-Thaw Cycle treatment after 40 days.

A different study performed by Azzam in 2002 investigated the influence of aggregate types, curing conditions, exposure conditions, and other factors on delayed ettringite formation. The results found in this study also illustrated that as the potassium content increased, the expansion increased for steam cured concretes. Similar results also were found for water cured specimens.

Chapter 3: Sample Preparation and Deteriorating Methods

3.1 Introduction

Mixing and casting of the specimens used in this research study took place at the Civil and Environmental Engineering Lab of the University of Maryland at College Park and at the National Ready Mix Concrete Association Laboratory in Greenbelt, Maryland. Based on previous research done by Ceesay in 2004 and McMorris et al in 2007, it was concluded that adding potassium to the concrete mixture can accelerate its deterioration. Therefore two batches were prepared; one batch was used as a control batch (Batch I), while the other batch was made with an additional 1.5% for a total of 2.06% of potassium carbonate per weight of cement (Batch II). Both batches were subjected to a deteriorating method either the UMD Modified Duggan Cycle, or one of two sets of Freeze-Thaw cycles. The degree of damage in the specimens was assessed by expansion tests, weight change measurements, change in Q-factors obtained through impact-echo testing, and compressive strength tests.

The goal of this study was to find correlations between Q-factors and the parameters mentioned above as the specimens deteriorate over time. Therefore, the initial measurements of expansion, weight change, and Q-factors were obtained after they were subjected to the UMD Modified Duggan Cycle. The initial measurements of the specimens used in the Freeze-Thaw cycles were taken before the first cycle was performed. The first compression strength test was done seven days after the Duggan Cycle and the rest were conducted at different intervals thereafter.

3.2 Specimen Preparation

3.2.1 Mix Design and Materials

Concrete specimens were prepared according to the ASTM C 192/C 192 M-06 standards for making and curing concrete specimens in the laboratory. An air-entrainment void system was not introduced into the concrete mixture since this would have reduced the effect of secondary ettringite formation (Day, 1992) and reduced the amount of deterioration. The concrete mix was proportioned using the Absolute Volume Method and prepared with a water to cement ratio of 0.5.

Two batches were prepared. Batch I acted as the control batch and was made with no varying parameters, and Batch II was made with an additional 1.5% for a total of 2.06% of potassium carbonate by weight of cement. Potassium carbonate was added to Batch II since the addition of potassium has been proven to increase ettringite growth and expansion by previous research studies. The amount of potassium carbonate (K_2CO_3) used in Batch II was approximately 338.42 grams. Both batches were proportioned and mixed in the same manner. The mixing information of each batch is summarized in Table 3.1.

Table 3.1: Mix Design

	Weight	
Water	24.89	lb
Cement	49.74	lb
Coarse Aggregate	111.60	lb
Fine Aggregate	81.62	lb

The cement used was quick hardening Type III cement obtained from a local supplier. This type of cement was chosen because it has been proven to increase expansion and deterioration (Ceesay, 2007). An x-ray fluorescence (XRF) spectroscopy performed on a small sample of the cement done by CTL Group in Skokie, Illinois, revealed that the cement already contained 0.56% of potassium (K_2O) by weight. The complete report of the spectroscopy is included in Figure 3.1 below. The potassium already in the cement was not taken into account or subtracted from the 1.5% potassium carbonate per weight of cement added. Therefore, Batch II contained a total of 2.06% of potassium per weight of cement. The potassium used was anhydrous granular reagent grade potassium carbonate (K_2CO_3) and it was dissolved into the mixing water of the concrete mix used for Batch II.

The aggregates used also were obtained from local suppliers. The coarse aggregate consisted of 1-inch maximum diameter limestone aggregate with a dry rodded weight of 102.3 lb/ft^3 , moisture absorption of 3%, and a specific gravity of 2.72. The fine aggregate was Frederick Stone Sand that conforms to ASTM C33-99a. The Frederick Stone Sand had moisture absorption of 1.0%, a specific gravity of 2.69, and is considered intermediate reactive.

Analyte	Weight %
SiO ₂	18.44
Al ₂ O ₃	4.86
Fe ₂ O ₃	3.36
CaO	58.46
MgO	3.87
SO ₃	2.73
Na ₂ O	0.13
K ₂ O	0.56
TiO ₂	0.30
P ₂ O ₅	0.11
Mn ₂ O ₃	0.31
SrO	0.06
Cr ₂ O ₃	0.03
ZnO	0.09
L.O.I. (950°C)	6.58
Total	99.90
Alkalies as Na ₂ O	0.50
Calculated Compounds per ASTM C 150-05.	
C3S	53
C2S	13
C3A	7
C4AF	10

Figure 3.1: Report of Chemical Analyses of Cement Used

3.2.2 Casting Procedure

Concrete specimens were prepared using steel prism molds and non-reusable PVC cylinders molds with lids in accordance to ASTM C192. The prisms prepared were 3” wide by 3” high by 11.25” long, and the cylinders were 4” in diameter and 8” long as seen in Figure 3.2. The steel prism molds had to be assembled with steel gage studs, for expansion measurements, using a rod so that 10 inches of space was available between them in accordance to ASTM C490 as shown by Figure 3.3. The prisms were used for expansion tests, weight change measurements and impact-echo testing, while the cylinders were used for compressive strength tests.



Figure 3.2: Steel Prism Molds and Non-reusable Cylinder Molds



Figure 3.3: Steel Gage Studs in Prisms

Motor oil was spread inside the molds with a sponge, as seen in Figure 3.4, to help the demolding process. The materials were proportioned in buckets using a mechanical scale and the potassium carbonate was measured on a digital metric scale and dissolved in the water used for Batch II. A rotating mixer with a capacity of 3.0 cubic feet was used to mix the concrete. After the concrete mixture was prepared, it was poured into the cylinder molds in two layers, rodding each layer 25 times and tapping the cylinders against the floor after each layer. The prisms were also tapped against the floor as the mixture was poured. Once this was complete, the specimens were struck off to obtain a finished smooth surface and either covered with aluminum foil (prisms) or covered with a lid (cylinders) to prevent drying and shrinkage, see Figure 3.5. A total of 28 concrete cylinders were prepared (14 for each batch) and 29 concrete prisms (15 for Batch I and 14 for Batch II).



Figure 3.4: Motor Oil Spread inside the Prism Molds with a Sponge



Figure 3.5: Specimens Covered with Aluminum Foil or Lids

3.2.3 Curing Method and Storage Condition

All 28 concrete cylinders, and 17 concrete prisms (9 from Batch I and 8 from Batch II) were steam cured directly after casting for four hours at 85 °C in a conventional oven. The concrete prisms (total of 12) which were not steam cured were used for Freeze-Thaw cycles and were room temperature cured. After curing, all the specimens were taken out of their molds and stored.

Based on the results found by Ceesay (2007), it was concluded that limewater was the ideal storage condition to accelerate deterioration in the specimens through ettringite growth. The specimens were stored, by fully submerging them, in plastic containers with limewater, as seen by Figure 3.6, at the Civil and Environmental Engineering Lab at College Park for approximately 18 days before subjecting them to either the UMD Modified Duggan Cycle or one of the two sets of Freeze-Thaw

cycles. The limewater was created by dissolving hydrated lime, obtained from a local supplier, into regular tap water. Once the Duggan Cycle was completed, the specimens were then returned to the limewater containers where they stayed for the remaining testing period.



Figure 3.6: Specimens Stored in Limewater

3.3 Deteriorating Methods

3.3.1 UMD Modified Duggan Heating Cycle

A total of 17 concrete prisms and 28 concrete cylinders were subjected to the UMD Modified Duggan heating cycle. This cycle has been proven to accelerate deterioration in concrete by initiating cracking and ettringite formation (Ceesay, 2007) and takes nine days to complete. The specimens were subjected to this heating

regime approximately 18 days after casting. Although in previous studies, the Duggan Cycle is initiated seven days after casting, the decision to wait 18 days was based on the conclusion made by Ramadan (2000) which found that extended periods of water storage can accelerate crack initiation time and maximize the rate of expansion.

The Duggan Cycle was carried out in the following manner. The specimens were placed in an oven at 82 °C for the first 24 hours. In the second day, the specimens were taken out of the oven and allowed to cool down for one hour and a half before storing them in water for another 24 hours. This process was repeated in the third and fourth day. In the fifth day, the specimens were placed in the oven at 82 °C for the next 72 hours. Once this heating period was over, the specimens were allowed to cool down for the last 48 hours. The initial measurements of expansion, weight change, and Q-factor were taken after the completion of this cycle and subsequent measurements were taken every three to five days for approximately five months.

3.3.2 Freezing-and-Thawing Cycles

The Freeze-Thaw cycles were carried out in two different sets and in accordance with ASTM C 666 standards. A total of 12 room temperature cured concrete prisms were used for freeze-thaw testing. The first set consisted of testing six concrete prisms in an Environmental Chamber, while the second set tested six concrete prisms in a Rapid Freeze-Thaw Cabinet apparatus.

The first set of freeze-thaw testing was performed on six concrete prisms, three from each batch, in an Environmental Chamber as the one seen Figure 3.7. The specimens were placed in a plastic container filled with tap water where they were

closely spaced and fully submerged. The chamber was programmed to run ten cycles continuously, each cycle lasting 12 hours to complete. A cycle consisted of lowering the temperature of the specimens from 4.4 °C to -18 °C during a two hour period, maintaining this temperature for the following four hours, raising it back to 4.4 °C during the next two hours, and keeping the temperature at 4.4 °C for the remaining four hours. The initial readings of expansion, weight change, and Q-factor measurements through impact-echo testing were taken at zero cycles and after every ten cycles thereafter until Q-factors could no longer be obtained.



Figure 3.7: Environmental Chamber Used

The second set of freeze-thaw testing was completed in a Rapid Freeze-Thaw Cabinet apparatus, see Figure 3.8 and Figure 3.9. In this test six concrete prisms were

used, three from each batch, and each cycle consisted of lowering the temperature from 4.4 °C to -18 °C and raising it back up to 4.4 °C. This apparatus was not programmable and therefore it was manually stopped after every three cycles for the first 30 cycles and after five cycles thereafter until the Q-factor values could no longer be obtained or until the specimens failed. The average amount of time to complete one cycle was approximately 5.4 hours. However, the actual amount of time varied since it depended on the condition of the specimens. As the prisms deteriorated, the cycles became shorter.



Figure 3.8: Rapid Freeze-Thaw Cabinet apparatus Used



Figure 3.9: Specimens in the Rapid Freeze-Thaw Cabinet apparatus

Chapter 4: Assessment Tests and Procedures

4.1 Assessment Tests

4.1.1 Introduction

All the testing done as part of this research study was carried out at the Civil and Environmental Engineering Lab of the University of Maryland in College Park. The change in the microstructure and the degree of damage in the concrete prisms caused by the UMD Modified Duggan Cycle was assessed every three to five days after the heating regime for approximately five months. The damage caused by the Freeze-Thaw cycles was assessed after ten, three, or five cycles. The assessment of these specimens consisted of recording the following data:

- Change in length
- Change in weight
- Change in Q-factor through impact-echo testing

In addition, compression strength tests were performed on cylinders from Batch I and Batch II which were subjected to the UMD Modified Duggan Cycle at specific intervals. The schedule of the compression strength tests is described in Table 4.1 below.

Table 4.1: Schedule of Compression Strength Tests

Time of Testing	Approximate age of specimen
7 Days from Duggan	30
30 Days from Duggan	60
90 Days from Duggan	120
120 Days from Duggan	150
150 Days from Duggan	180

4.1.2 Number of Specimens Used

Although a total of 29 concrete prisms (15 from Batch I and 14 from Batch II) were prepared, only 24 prisms were used for the assessment tests described above. The freeze-thaw damage was assessed by testing 12 concrete prisms, however only 12 of the available 17 were used to monitor the damage caused by the Duggan Cycle. The remaining five specimens were kept in limewater and set apart. A summary of the specimens used in testing is described in Table 4.2.

Table 4.2: Total Number of Specimens Used in Testing

	Batch I	Batch II
Duggan Cycle		
- Prisms	6	6
- Cylinders	14	14
Freeze-Thaw Cycles		
- Prisms (Environmental Chamber)	3	3
- Prisms (Freeze-Thaw Cabinet)	3	3

4.2 Procedures

4.2.1 Expansion Test

Expansion measurements were taken in accordance with ASTM C 157 Standard Test Method for Length Change of Hardened Mortar and Concrete with a digital comparator accurate to ± 0.0001 inches see Figure 4.1. The initial measurements were taken after the completion of the UMD Modified Duggan Cycle and before any Freeze-Thaw cycles were done. Subsequent readings were taken every three to five days (Duggan specimens), or after a specific number of Freeze-Thaw cycles (Freeze-Thaw specimens). The expansion measurements were made relative to

a 10" long bar after the specimens were taken out of the water and the excess water was removed with a towel. The equation used to calculate expansion percentage was calculated using:

$$\Delta L = \frac{(L_x - L_i)}{G} \times 100$$

ΔL = length change of the specimen at any age, %

L_x = comparator reading of specimen at x age minus comparator reading of reference bar at x age, inches

L_i = initial comparator reading of specimen minus comparator reading of reference bar at that same time, inches

G = nominal gage length, 10 inches



Figure 4.1: Comparator Used for Expansion Tests

4.2.2 Weight Change Measurements

Weight change measurements were done along with the expansion measurements. The initial measurements were taken after the completion of the UMD Modified Duggan Cycle and before any Freeze-Thaw cycles were done. A digital scale with an accuracy of ± 0.1 gram was used, see Figure 4.2. The specimens were taken out of the water, dried off with a towel, and weighted. The equation used for the percentage weight change was:

$$\Delta W = \frac{(W_x - W_i)}{W_i} \times 100$$

ΔW = weight change of the specimen at any age, %

W_x = weight of specimen at x age

W_i = initial weight of specimen



Figure 4.2: Scale Used for Weight Change Measurements

4.2.3 Impact-Echo Test

Impact-echo testing was done every time weight and expansion measurements were taken. The specimens were tested using the standard method as set in AASHTO Designation TP18: *Standard Test Method for Determining the Fundamental Transverse Frequency and Quality Factor of Concrete Prism Specimens*.

The impact-echo apparatus used consisted of a Fourier Analyzer, an impact hammer, an accelerometer and power supply, a specimen support base, and a computer with Virtual Bench software, see Figure 4.3. The hammer was equipped with a tip of sufficient hardness and appropriate shape so as not to damage the concrete when used to impact it. It also contained an electronic load cell and a power supply capable of producing an output voltage that is proportional to the magnitude of the impact with the specimen. The accelerometer used was approximately 3/8 of an inch in diameter with a flat base and was attached to the specimens during testing using vacuum grease. The impact hammer and accelerometer are shown in Figure 4.4. The specimen support base is made up of two parallel piano wires of 0.0244-inches (0.62 mm) in diameter that allow the specimen to vibrate freely and minimize the amount of vibration energy absorbed from the specimen itself, see Figure 4.5. The wires were set up to support the specimen at a specific distance from each end of the specimen. Virtual Bench software was used to control the equipment and to record and store the data and OriginPro software was used to analyze the data.

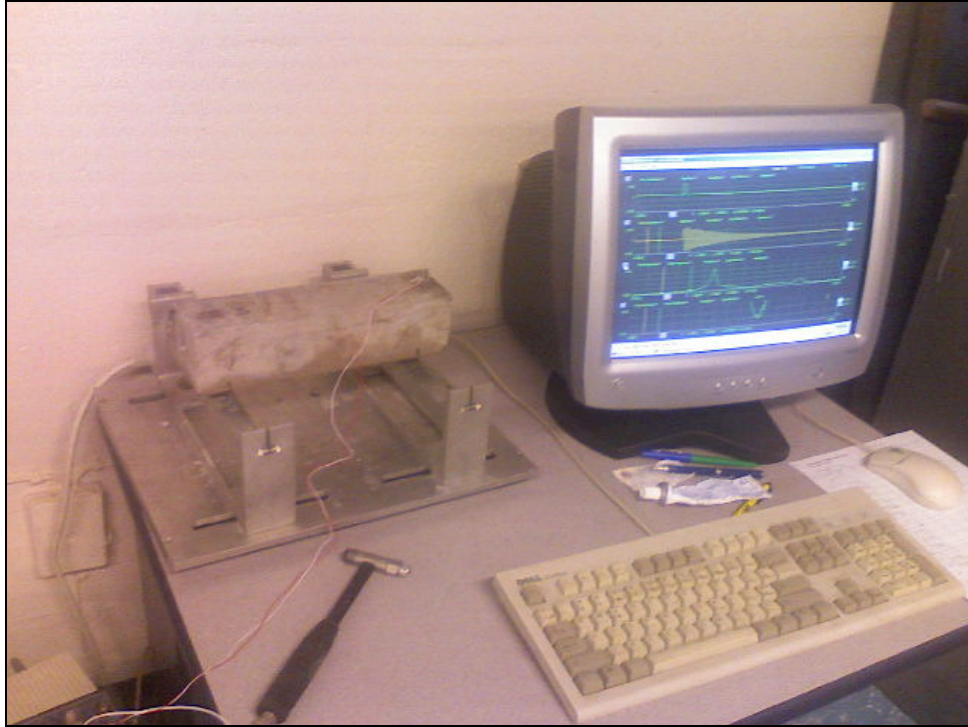


Figure 4.3: Impact-echo Apparatus



Figure 4.4: Impact Hammer and Accelerometer of Impact-echo apparatus

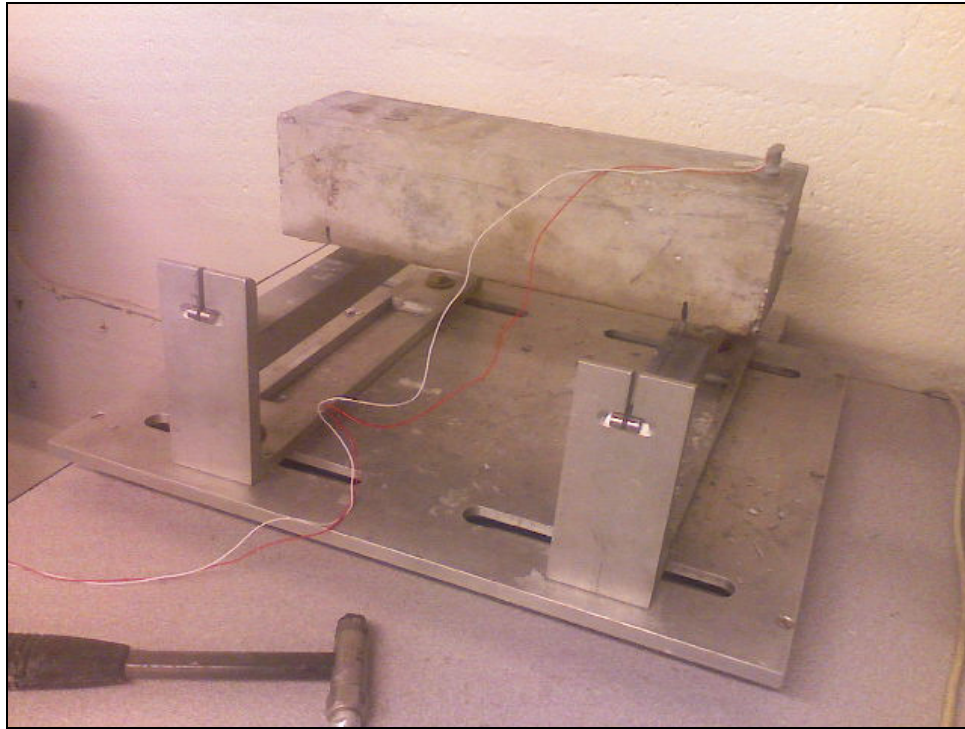


Figure 4.5: Impact-echo Support Base

The procedure used with this impact-echo device was different than that used by commercial products in the field. Testing a specimen consisted of centering it on the supporting wires in such a way as to have equal ends extending beyond the wire. The location of the wires was marked on all the specimens to keep the set up of each and their alignment consistent throughout the testing period. The accelerometer was attached to the top surface of the specimen as close to one end as possible using vacuum grease. Securing the accelerometer in the specimen was important in order to prevent irregularities in the response curve. After setting the specimen in place, a vertical impact was applied centered on the top surface and on the opposite end to where the accelerometer was attached. The impact was applied as near the end of the specimen as possible. The responses from the impact hammer and the accelerometer

were recorded using Virtual Bench software. At least three impacts on the specimens were applied before recording a final response, stopping vibrations between impacts, to observe a consistent response and a smooth shape. It was important to stop the vibrations between impacts because these can cause irregularities in the data. It was expected that as the specimens deteriorated, the response curve would become less smooth due to internal cracking.

4.2.4 Compression Strength Test

Compression strength tests were performed in accordance with ASTM C39 standards on 24 concrete cylinders (12 from each batch) which were subjected to the Duggan Cycle. A machine with a 400,000 lbs capacity was used, as shown in Figure 4.6. The specimens were removed from the limewater, dried off with a paper towel, and measured (diameter measurements) before testing them at a load rate of approximately 25,000 lb/min. These tests were done at 7, 30, 90, 120, and 150 days (± 2 day) after the completion of the Duggan Cycle as described in Table 4.1 in Chapter 4. The compressive strength reported in the graphs in Chapter 6 is the average compressive strength of the specimens tested at the different intervals.



Figure 4.6: Compression Strength Testing Machine Used

Chapter 5: Test Results

5.1 Introduction

The changes in expansion, weight, and Q-factors of concrete specimens subjected to two different types of deteriorating methods were analyzed in this research study. In addition, the effect of adding potassium carbonate to accelerate deterioration also was investigated. The deteriorating methods included the UMD Modified Duggan Cycle and two sets of Freeze-Thaw cycles. Compression strength tests also were performed on the specimens subjected to the Duggan Cycle. Prism specimens subjected to the heating regime were tested for expansion, weight change, and Q-factor change through impact-echo testing for approximately five months, and specimens subjected to Freeze-Thaw cycles were tested until failure or until the Q-factors from the impact-echo testing could no longer be obtained due to heavy deterioration. Concrete cylinders were used for compression strength tests done at different intervals as described in Table 4.1 in Chapter 4. Two batches were prepared, Batch I with no varying parameters, and Batch II, which contained an additional 1.5% of potassium carbonate by weight of cement. According to spectroscopy findings, the amount of potassium (K_2O) already found in the cement used was 0.56% by weight of cement. Therefore, Batch II contained a total of 2.06% of potassium by weight of cement.

5.2 Expansion Test Results

5.2.1 Duggan Cycle Batch I and Batch II

Six prism specimens from Batch I subjected to the Duggan Cycle were used for expansion measurements. Batch I served as the control batch and was prepared with no varying parameters. The initial measurements were taken after the completion of the Duggan Heat Cycle and every three to five days thereafter. A plot of the expansion change of each specimen from Batch I versus the concrete age after the heating regime is shown in Figure A.1 in the Appendix. The expansion at 21 days of Batch I was 0.0057%, which is much smaller than the threshold value of 0.05% expansion suggested by the Duggan test as pass/fail criteria for concrete. This implies that the concrete does not have the potential to deteriorate due to DEF. However, this threshold value is intended for smaller concrete cores and therefore it is not applicable in this case. The maximum average expansion change achieved by Batch I was 0.0153%, which occurred at day 90 after the Duggan Cycle had ended. There was little variation in the expansion change measurements after 44 days. The expansion at 150 days was 0.0102%. The expansion found in a similar study of heat cured concrete with 0.72% of potassium by weight of cement (Ramadan, 2000) at 150 days after the Duggan Cycle was 0.03125%. The expansion change at 150 days after the completion of the Duggan Cycle by the control batch (with 0.82% of potassium by weight of cement) in a different study carried out by Ceesay in 2007 was approximately 0.0852%. These values are much larger than the expansion change experienced by Batch I in this research study. However, this is expected as each study

used cements with different amounts of potassium carbonate and different fine aggregates.

The expansion change measurements from Batch II were also taken from six prism specimens starting at the completion of the Duggan Cycle. Batch II contained a total of 2.06% of potassium by weight of cement. A plot of the expansion change observed from Batch II versus the concrete age is shown in Figure A.2 in the Appendix. The expansion change from Batch II increased steadily with time which was very different than the expansion change pattern observed from Batch I. The 21 day expansion of Batch II was 0.0097%, which did not exceed the Duggan threshold value and implies that the concrete does not have the potential to deteriorate due to DEF. However, it should be noted that the Duggan threshold is intended for smaller concrete cores suggesting that larger prisms should have a lower threshold value since it has been found that the sample size affects the time to the start of expansion (Heinz and Ludwig, 1987). The maximum average expansion of Batch II was 0.0700% and it occurred at 150 days after the Duggan Cycle. The expansion at 150 days after the Duggan Cycle found in a similar study by Azzam (2002) of steam cured concrete specimens with a total of 2.1% potassium carbonate per weight of cement was approximately 0.5500%. Another similar study (Ramadan, 2000) of heat cured concrete with 2.1% of potassium carbonate by weight of cement revealed an expansion of 0.8250% at 150 days after the Duggan Cycle. These expansions are much larger than the values found in this study. However, this is expected as different amounts of potassium carbonate and different fine aggregates were used in each study. The study by Azzam (2002) used Medford Sand which was considered to be

nonreactive according to the Maryland State Highway Administration, the study by Ramadan (2000) used Natural Sand which was considered to be mildly reactive, and this study used Fredrick Stone Sand which was considered to be intermediate reactive. It has been found that the aggregate reactivity plays an important role in the expansion of concrete (Heinz and Ludwig 1989, and Diamond and Ong 1993).

A plot comparing the expansion change of Batch I and Batch II is shown in Figure 5.1. It is evident from this plot that the addition of potassium carbonate greatly increases the expansion change in specimens subjected to the Duggan Cycle.

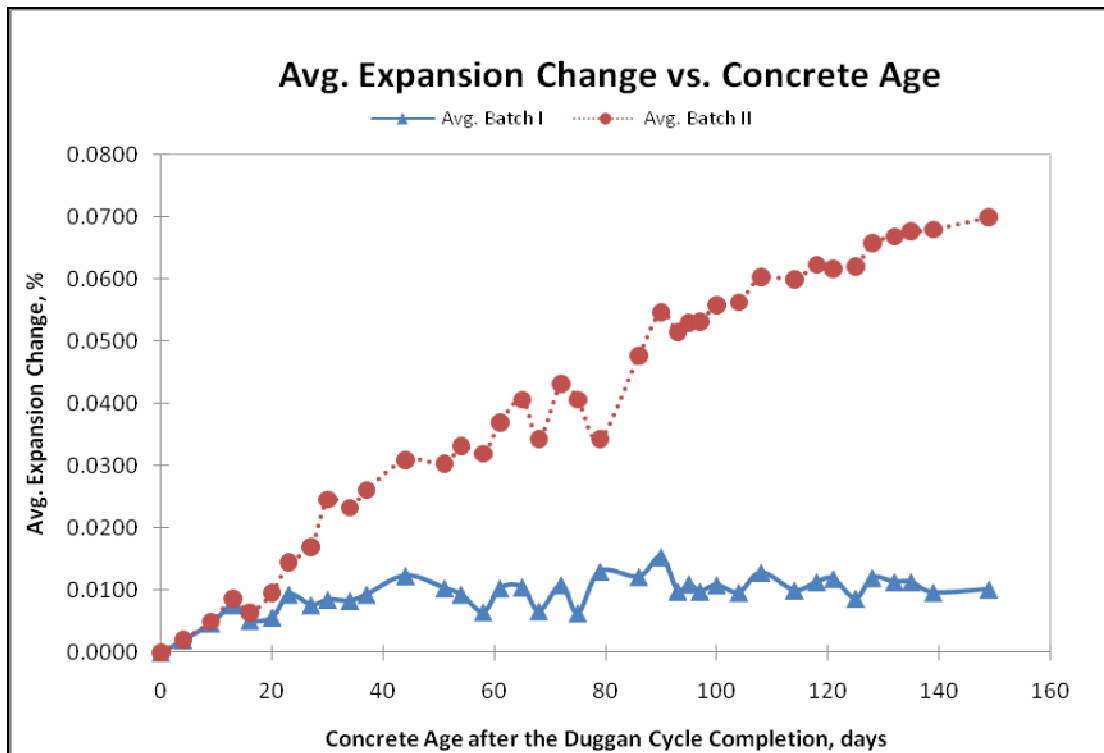


Figure 5.1: Expansion Change Comparison of Duggan Specimens

5.2.2 Environmental Chamber Freeze-Thaw Batch I and Batch II

Freeze-thaw testing was carried out in two different sets. The first set consisted of testing six specimens using an Environmental Chamber, three from

Batch I and three from Batch II. The expansion change measurements on these specimens were taken every ten cycles. All measurements were taken until Q-factors from the impact-echo testing were no longer obtainable.

The concrete specimens from Batch I tested in the Environmental Chamber were able to endure a total of 60 cycles. The maximum average expansion change of the specimens from Batch I was 1.0037%. Figure A.3 in the Appendix shows the expansion change versus the number of cycles acquired for all three specimens of Batch I. Although the specimens from this batch were still intact after 60 cycles, expansion change measurements had to be stopped because the specimens were very fragile and heavily deteriorated. Consequently, fundamental frequencies were no longer evident from the impact-echo results and Q-factor values could no longer be calculated.

Two of the three specimens from Batch II tested in the Environmental Chamber were able to endure a total of 40 cycles, and one endured 50 cycles. The maximum average expansion change of the specimens from Batch II was 1.4760%, which is 47% higher than the maximum expansion experienced by the specimens from Batch I. Figure A.4 in the Appendix shows the expansion change of all three specimens from Batch II. Unlike the specimens from Batch I, these specimens deteriorated to the point of breaking into pieces.

A comparison between the expansion change versus the number of cycles of Batch I and Batch II is shown in Figure 5.2. The findings represented by the graph prove that the addition of potassium carbonate to Batch II accelerated deterioration since those specimens revealed greater expansion changes.

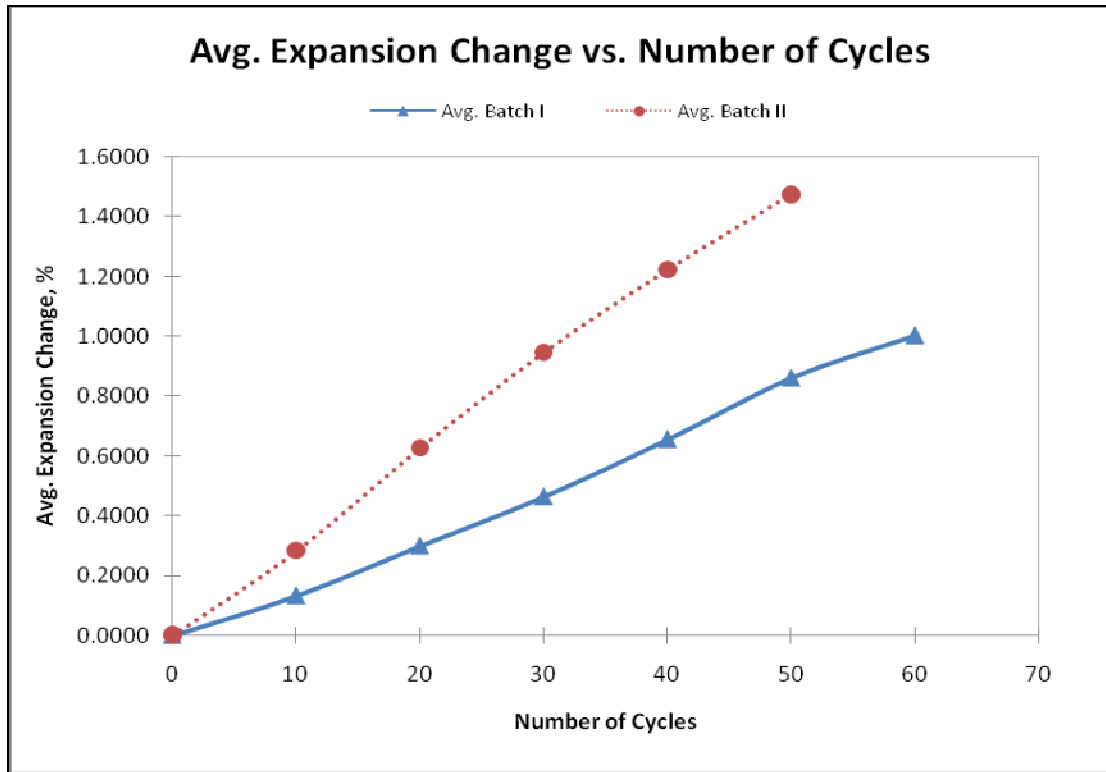


Figure 5.2: Expansion Change Comparison of Environmental Chamber Specimens

5.2.3 Cabinet Apparatus Freeze-Thaw Batch I and Batch II

As previously stated, freeze-thaw testing was carried out in two different sets. The second set of freeze-thaw testing was performed on six specimens, three from each batch, using a Rapid Freeze-Thaw Cabinet apparatus. The expansion measurements of these specimens were done every three cycles for the first 30 cycles and every five cycles thereafter until Q-factor measurements through impact-echo testing could no longer be obtained.

One of the three specimens from Batch I subjected to Freeze-Thaw cycles in the Rapid Freeze-Thaw Cabinet apparatus was able to endure a total of 100 cycles, and the other two were able to complete 105 cycles. Figure A.5 in the Appendix shows the expansion change versus the number of cycles observed from these

specimens. The maximum average expansion change reached by the specimens of Batch I was 1.2455%, which occurred at the end of the 105th cycle.

The specimens from Batch II did not endure as many cycles as the ones from Batch I. Two specimens were able to endure a total of 90 cycles, while one was able to complete 100 cycles. A plot of the expansion change versus the number of cycles of all three specimens from Batch II is shown in Figure A.6 in the Appendix. The maximum average expansion of Batch II was found to be 1.3500%, which occurred at the end of the 100th cycle. The maximum expansion reached by the specimens from Batch II was only 8% higher than the maximum expansion reached by Batch I.

A plot comparing the expansion change observed versus the number of cycles endured by Batch I and Batch II is shown in Figure 5.3. This graph illustrates that the addition of potassium carbonate to Batch II accelerated deterioration and resulted in higher expansion changes, though not as high as the ones observed by the specimens subjected to the Freeze-Thaw cycles in the Environmental Chamber and the specimens subjected to the Duggan Cycle.

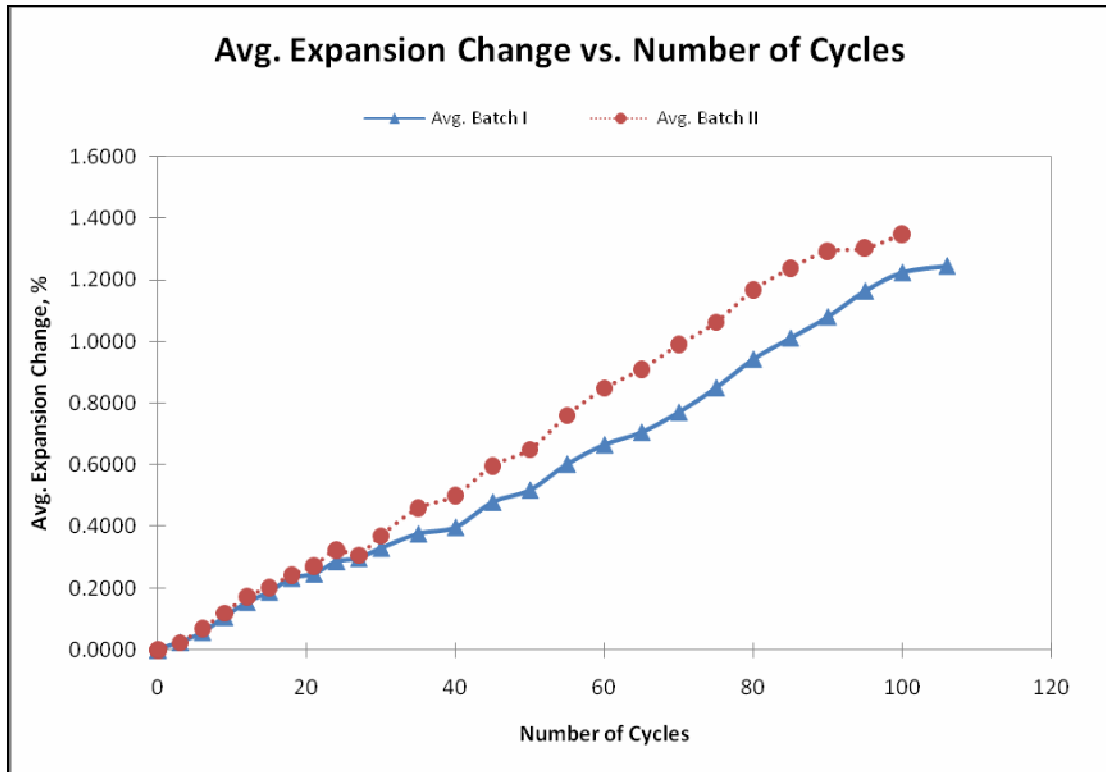


Figure 5.3: Expansion Change Comparison of Freeze-Thaw Cabinet Specimens

5.3 Weight Change Measurement Results

5.3.1 Duggan Cycle Batch I and Batch II

The weight change measurements of twelve prism specimens, six from each batch, subjected to the UMD Modified Duggan Cycle were taken every three to five days along with the expansion change measurements.

Batch I was the control batch and was prepared with no varying parameters. Figure A.7 in the Appendix shows the weight change versus the concrete age of all six specimens from Batch I. The maximum average weight change achieved by Batch I was 0.5913% which occurred at 128 days after the completion of the Duggan Cycle. It was observed that the weight change of the specimens from Batch I increased steadily with time.

The weight change measurements of specimens from Batch II were done using six concrete prisms, each containing a total of 2.06% of potassium carbonate by weight of cement. Figure A.8 in the Appendix shows the weight change versus the concrete age of the specimens from Batch II after the completion of the Duggan Cycle. The weight change of the specimens from Batch II increased steadily with time and was very similar to that of Batch I. The maximum average weight change observed by Batch II was 0.6893% at 150 days after the completion of the Duggan Cycle.

A plot comparing the weight change versus the concrete age of Batch I and Batch II is shown in Figure 5.4. As can be seen from this plot, the addition of potassium carbonate had little effect in the weight change since both batches displayed similar weight change patterns. However, the gap between Batch I and Batch II seemed to increase with time after day 80.

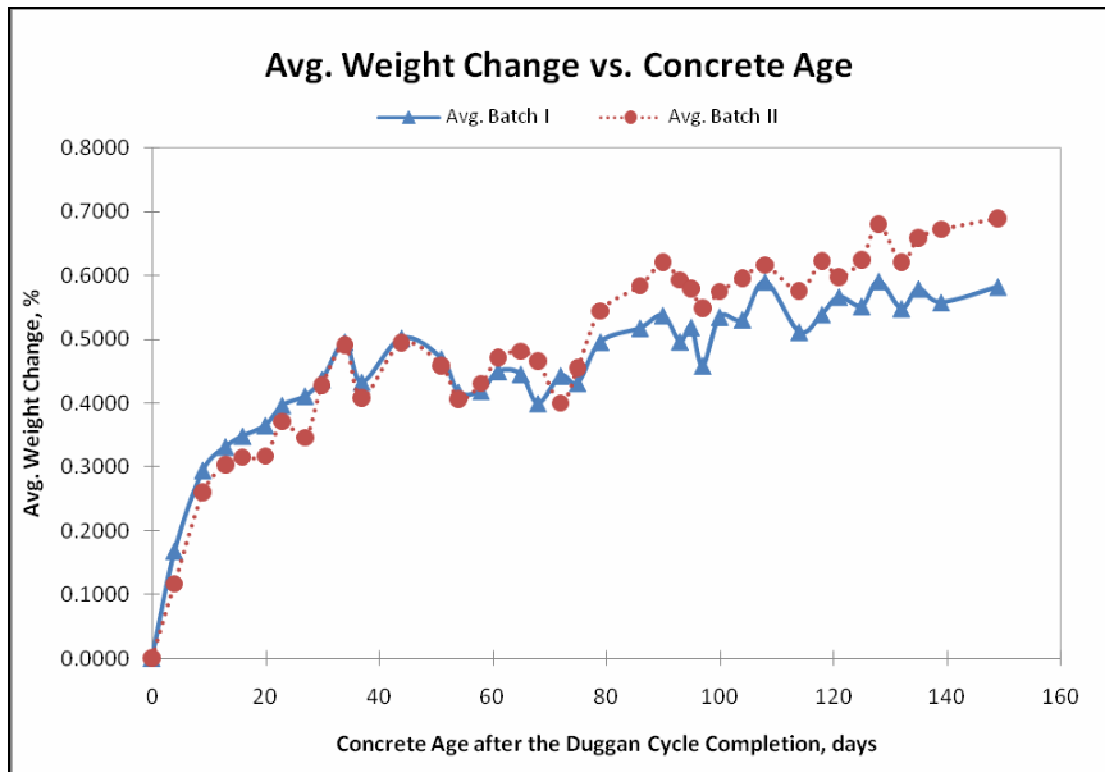


Figure 5.4: Weight Change Comparison of Duggan Specimens

5.3.2 Environmental Chamber Freeze-Thaw Batch I and Batch II

As mentioned earlier, three specimens from each batch were subjected to Freeze-Thaw cycles in an Environmental Chamber. The weight change measurements of these specimens were taken along with the expansion change measurements, every ten cycles. Weight change measurements and all other measurements were taken until the Q-factors from the impact-echo testing could no longer be obtained.

All three specimens from Batch I endured 60 cycles before measurements were stopped. The maximum average weight change of the specimens from Batch I was 0.9453%, which occurred after the 60th cycle was completed. Figure A.9 in the Appendix shows the weight change versus the number of cycles obtained of all three specimens from Batch I.

Most of the specimens from Batch II were able to endure 40 cycles and one was able to withstand 50 cycles. A plot of the weight change over the number of cycles observed from all three specimens of Batch II is shown in Figure A.10 in the Appendix. The maximum average weight change of Batch II was found to be 1.8306%, which was measured after the completion of the 40th cycle. The maximum weight change of the specimens from Batch II was 93% higher than the maximum weight change of the specimens from Batch I.

A comparison of the weight change observed versus the number of cycles endured by Batch I and Batch II is shown in Figure 5.5. As can be seen from the plot, the addition of potassium carbonate in Batch II accelerated deterioration and resulted in greater weight change measurements than those observed by Batch I.

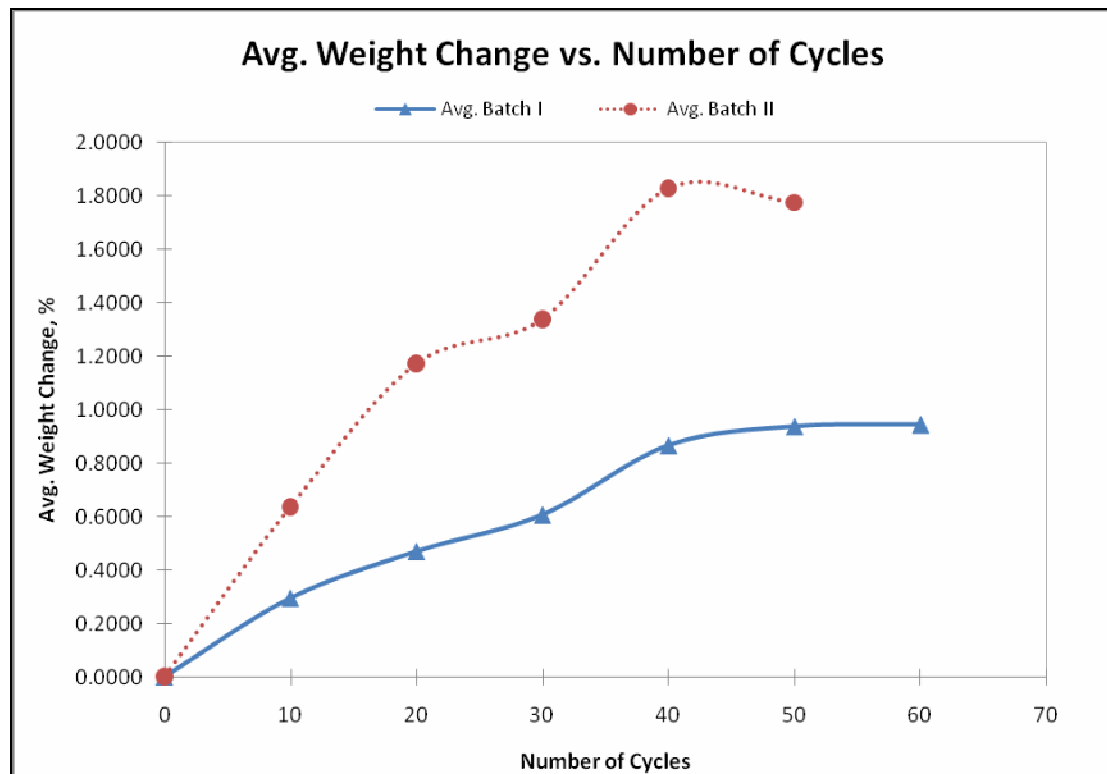


Figure 5.5: Weight Change Comparison of Environmental Chamber Specimens

5.3.3 Cabinet Apparatus Freeze-Thaw Batch I and Batch II

A total of six concrete prism specimens, three from each batch, subjected to Freeze-Thaw cycles in the Rapid Freeze-Thaw Cabinet apparatus were used for weight change measurements. The weight measurements were conducted along with expansion measurements, every three cycles for the first 30 cycles and every five cycles thereafter until failure or until Q-factors could no longer be obtained.

Most of the specimens from Batch I were able to endure a total of 105 cycles; however one specimen completed only 100 cycles. Figure A.11 in the Appendix shows the weight change observed over the number of cycles endured for all three specimens from Batch I. The weight change in this batch increased until the 80th cycle achieving a maximum average weight change of 1.8518%. However, after the 80th cycle the specimens started to experience loss of concrete due to heavy deterioration and the weight change measurements started to decrease.

The specimens from Batch II were able to endure fewer cycles than those from Batch I, two reached 90 cycles while one reached 100 cycles. A plot of the weight change versus the number of cycles endured by the three specimens from Batch II is shown Figure A.12 in the Appendix. The maximum average weight change of Batch II was found to be 1.6959% at the end of the 75th cycle. However, as with Batch I, the specimens from Batch II started to experience loss of concrete due to deterioration after the completion of the 75th cycle and the weight change measurements decreased. The weight change of Batch II started to decrease more rapidly than the weight change of Batch I.

A plot comparing the weight change observed of the specimens from Batch I and Batch II is shown in Figure 5.6. It can be observed from this plot that the addition of potassium carbonate in Batch II did not result in significantly greater weight changes than the ones observed by Batch I. However, the potassium carbonate did accelerate deterioration in the specimens from Batch II since those specimens started to deteriorate before the specimens from Batch I.

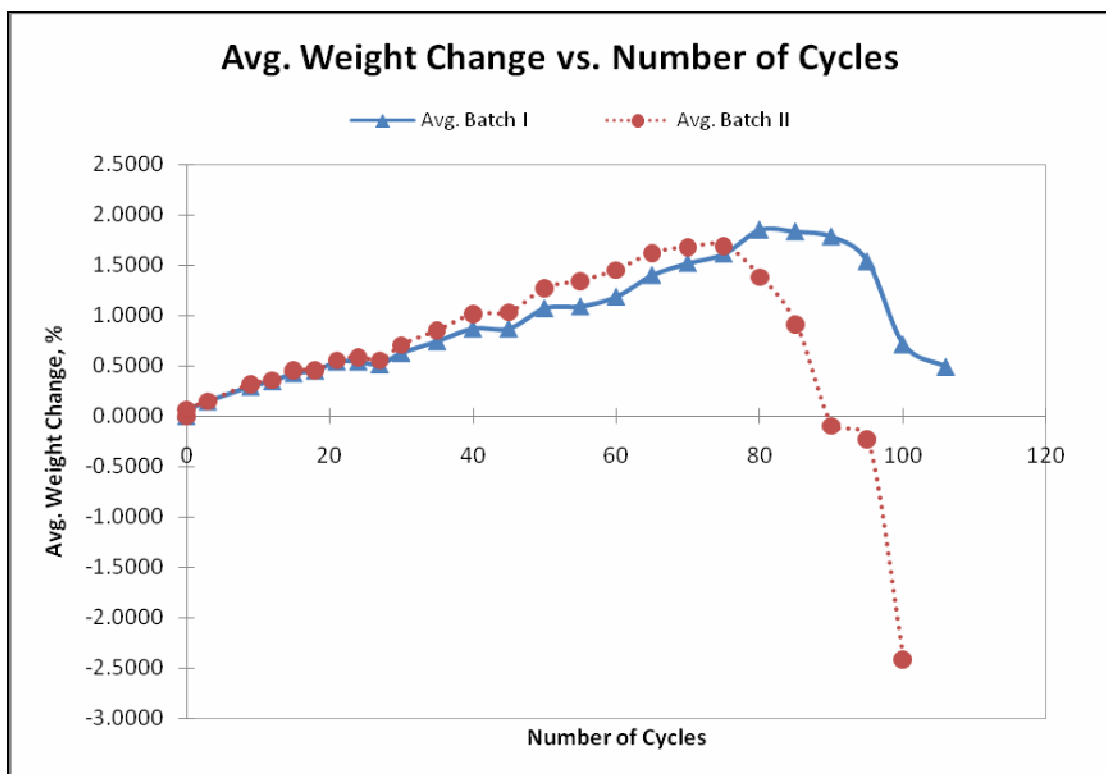


Figure 5.6: Weight Change Comparison of Freeze-Thaw Cabinet Specimens

5.4 Q-factor from Impact-echo Results

5.4.1 Duggan Cycle Batch I and Batch II

The Q-factors from the specimens subjected to the Duggan Cycle were acquired through impact-echo testing, which was performed along with expansion

and weight change measurements every three to five days after the completion of the heating regime. The Q-factors were calculated using a Lorentzian fit curve, since this curve has been shown by previous research (McMorris et al, 2007) to be a good fit for this type of data.

Overall, the Q-factors calculated from these specimens did not vary much over the five months that they were observed. Figure 5.7 shows the average Q-factors from Batch I and Batch II plotted versus the concrete age after the completion of the Duggan Cycle. It can be observed from the plot that the Q-factors from Batch II were lower than those obtained by Batch I. This is probably due to deterioration through DEF and ASR caused by the addition of potassium carbonate to Batch II. While the Q-factors from both batches did not seem to change significantly, the Q-factor values from Batch II seem to slightly decrease over time. This observation is based on the slight increase in the gap difference between the two batches that can be observed from the plot. The standard deviation, a measure of the data spread about the mean, of Batch I was found to be 1.0933, while the standard deviation of Batch II was 1.0546. This confirmed that the Q-factors obtained from both batches did not vary much over the length of the research study.

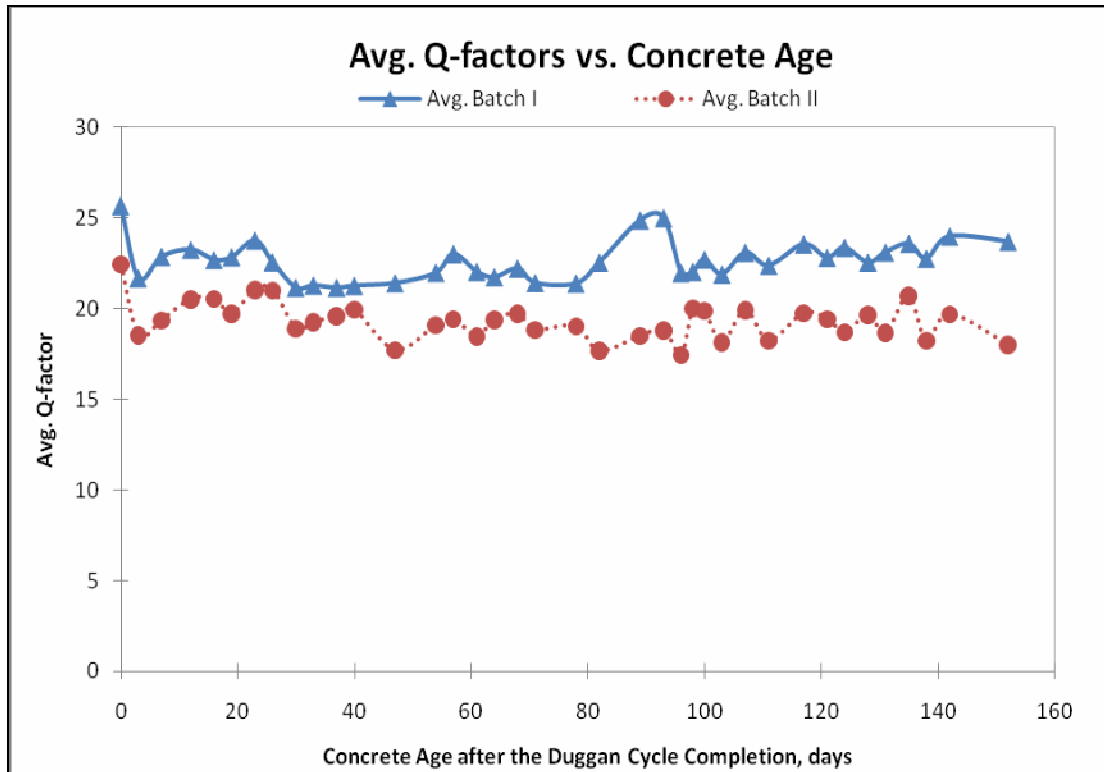


Figure 5.7: Q-factor Change of Duggan Specimens

5.4.2 Environmental Chamber Freeze-Thaw Batch I and Batch II

The Q-factors from the specimens subjected to the Freeze-Thaw cycles in the Environmental Chamber were obtained through impact-echo testing done along with expansion and weight change measurements every ten cycles. The initial Q-factor measurements were calculated before any cycles were performed. It was observed that the Q-factors obtained from these specimens decreased every ten cycles. The decrease indicates an increase in structural deterioration and an increase in freeze-thaw deterioration. Figure 5.8 shows a plot of the Q-factors versus the number of cycles of the specimens from Batch I and Batch II. As can be seen from the plot, the Q-factors from Batch II were lower than those of Batch I probably due to the specimens' deteriorated condition caused by the addition of potassium carbonate to

Batch II. The gap difference between the two batches seems to remain consistent over the number of cycles.

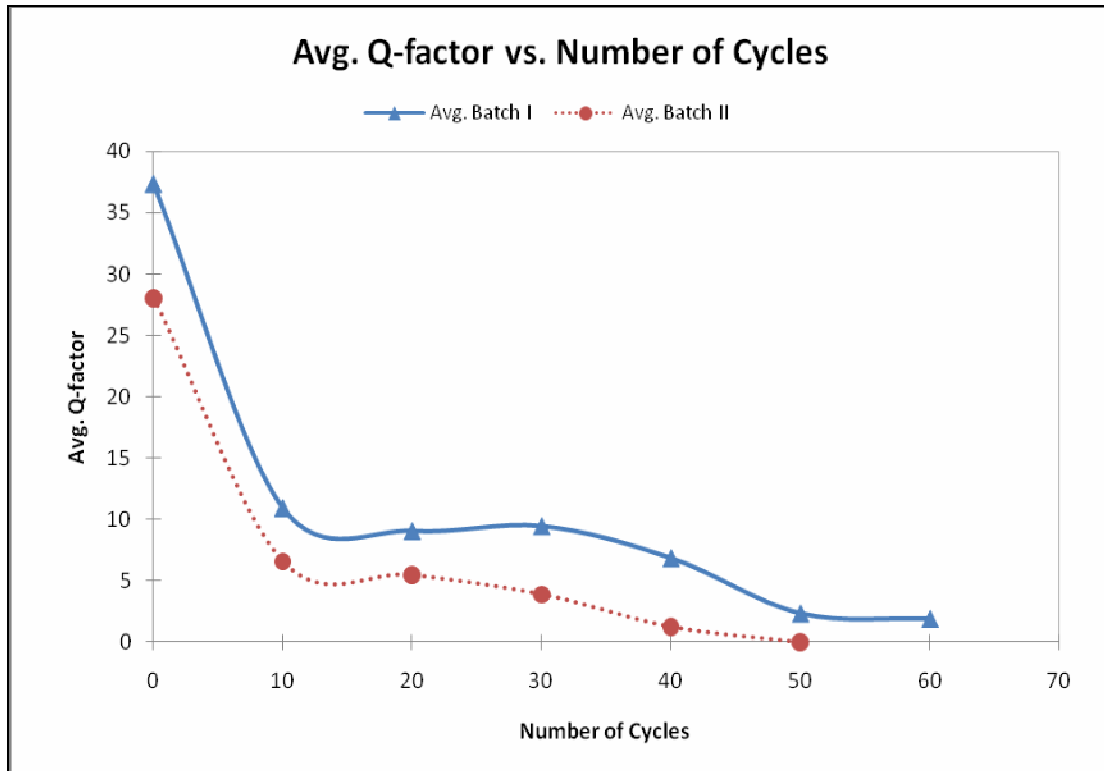


Figure 5.8: Q-factor Change of Environmental Chamber Specimens

5.4.3 Cabinet Apparatus Freeze-Thaw Batch I and Batch II

The Q-factors from the specimens subjected to Freeze-Thaw cycles in the Rapid Freeze-Thaw Cabinet apparatus were calculated from data of the impact-echo testing that was gathered along with expansion and weight change measurements every three cycles for the first 30 cycles and every five cycles thereafter. It was observed that the Q-factors from these specimens also decreased after each group of cycles, which indicates structural deterioration. Figure 5.9 shows the plot of the Q-factors found versus the number of cycles endured by the specimens from Batch I and

Batch II. The plot revealed that the Q-factors from Batch I and Batch II were similar to each other. However, the Q-factors of Batch II were still lower than those of Batch I, which implies that the addition of potassium carbonate accelerated deterioration in this batch.

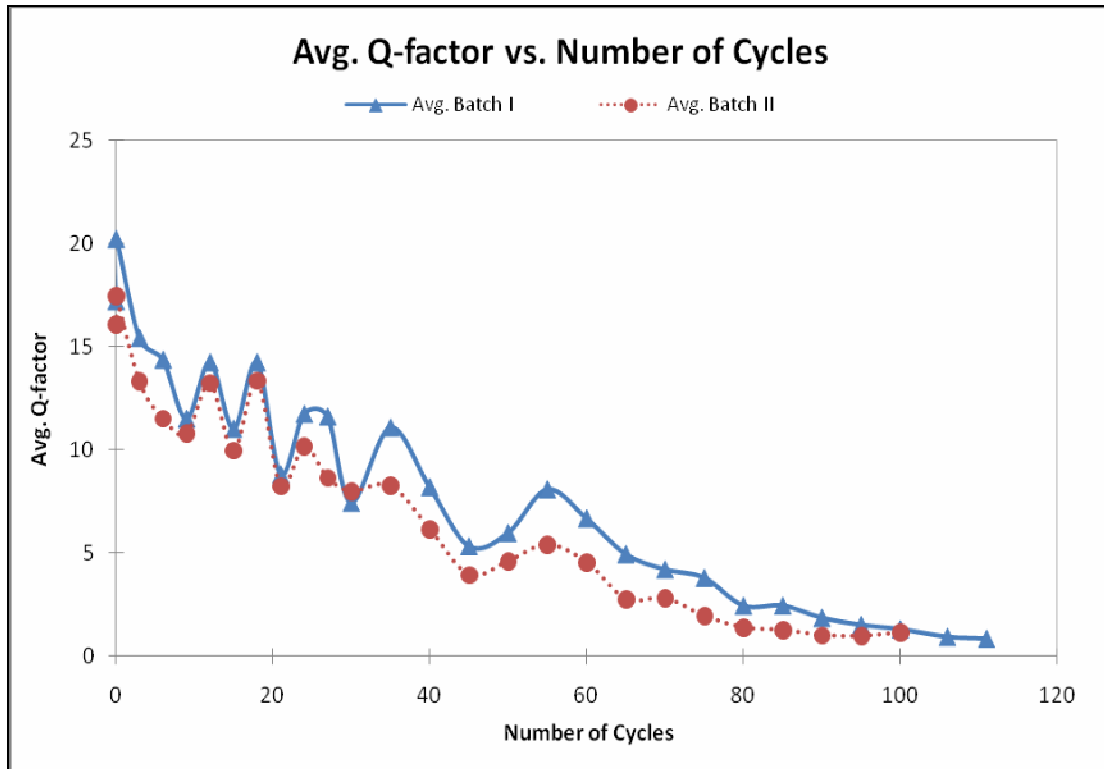


Figure 5.9: Q-factor Change of Freeze-Thaw Cabinet Specimens

5.5 Compression Strength Test Results

5.5.1 Duggan Cycle Batch I and Batch II

Compression strength tests were carried out using concrete cylinders, 12 from Batch I and 12 from Batch II, at different intervals as described in Table 4.1 in Chapter 4. Figure 5.10 shows the results obtained from the compression strength tests with error bars (standard deviation), and Table 5.1 provides a detailed summary of

these results. The addition of potassium to Batch II had a significant effect in the concrete's compressive strength, while the strength of Batch I increased over time, the strength of Batch II did not increase as much and started to decrease after 120 days of the completion of the Duggan Cycle. At 150 days after the completion of the heating regime, Batch II showed a 10% reduction in strength while Batch I revealed a 27% increase.

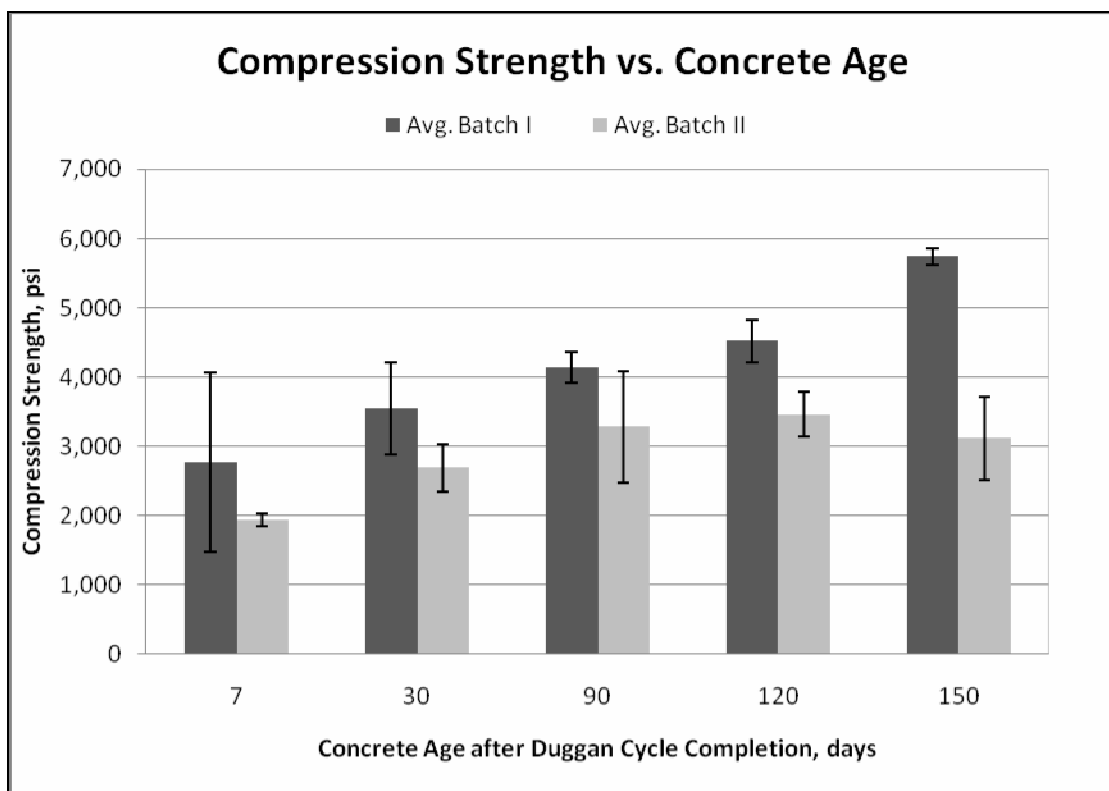


Figure 5.10: Compression Strength of Duggan Specimens with Error Bars

Table 5.1: Summary of Compression Strength of Duggan Specimens

Days after Duggan	Compression Strength, psi	
	Batch I	Batch II
7	2768	1940
30	3550	2688
90	4146	3280
120	4524	3461
150	5739	3115

The compressive strength at 30 days after the Duggan Cycle was found to be 3550 psi and 2688 psi, for Batch I and Batch II respectively. A similar study performed by Ceesay (2007) of heat-cured concrete specimens with 0.82% of potassium carbonate by weight of cement (control batch) subjected to the Duggan Heat Cycle and stored in limewater found a compressive strength of 5182 psi at day 28. In that same study, a batch with a total of 1.5% of potassium carbonate by weight of cement revealed a compressive strength of 4521 psi at 28 days after the Duggan Cycle. The compressive strength of Batch I found in this study is low when compared to the control batch of the study performed by Ceesay (2007). However, the amount of potassium carbonate in the cement used for the control batch in the study by Ceesay (2007) was 46% higher than the amount of potassium carbonate in the cement used for the control batch of this study. The compressive strength of Batch II was much lower than the one found from the batch containing 1.5% of potassium carbonate by weight of cement in the study by Ceesay (2007). It should also be taken into consideration that there was a difference in the total amount of potassium carbonate used and that there was a difference in the amount of time between casting

and starting the Duggan Cycle between these two studies. Specimens in this study were stored in limewater for approximately 18 days before subjecting them to the heat cycle, whereas the specimens in the other study was subjected to the cycle 7 days after casting. Another difference between these two studies was the storage condition. The specimens in the study by Ceesay (2007) were stored in limewater which was monitored and maintained at a pH of 12.5. The specimens in this study were stored in limewater as well, but the water used was not monitored or maintained at any specific pH value.

5.6 Correlation with Q-factors from Impact-Echo Results

The main goal of this research study was to investigate a correlation between the expansion change, weight change, and compressive strength to the Q-factors obtained through impact-echo testing. Linear regression analyses were performed to find correlations between these parameters. All plots below display the equation of the best fit line as well as the coefficient of determination value (R^2). The R^2 value was used to interpret the strength of the correlation.

5.6.1 Duggan Cycle Batch I and Batch II:

5.6.1.1 Expansion Correlation

The first correlation sought of the specimens subjected to the UMD Modified Duggan Cycle was one between expansion change and Q-factor values. Figure 5.11 shows a plot of the average Q-factors obtained versus the expansion change observed in Batch I and Batch II. As mentioned earlier, the expansion change and the Q-factors

of Batch I did not vary much over the period of the research study. Therefore, as can be seen from the plot, the data for this batch was mostly concentrated in one area. However, there was more variation observed in Batch II. Linear regression analyses were performed and plotted in Figure 5.12 and Figure 5.13, for Batch I and Batch II respectively.

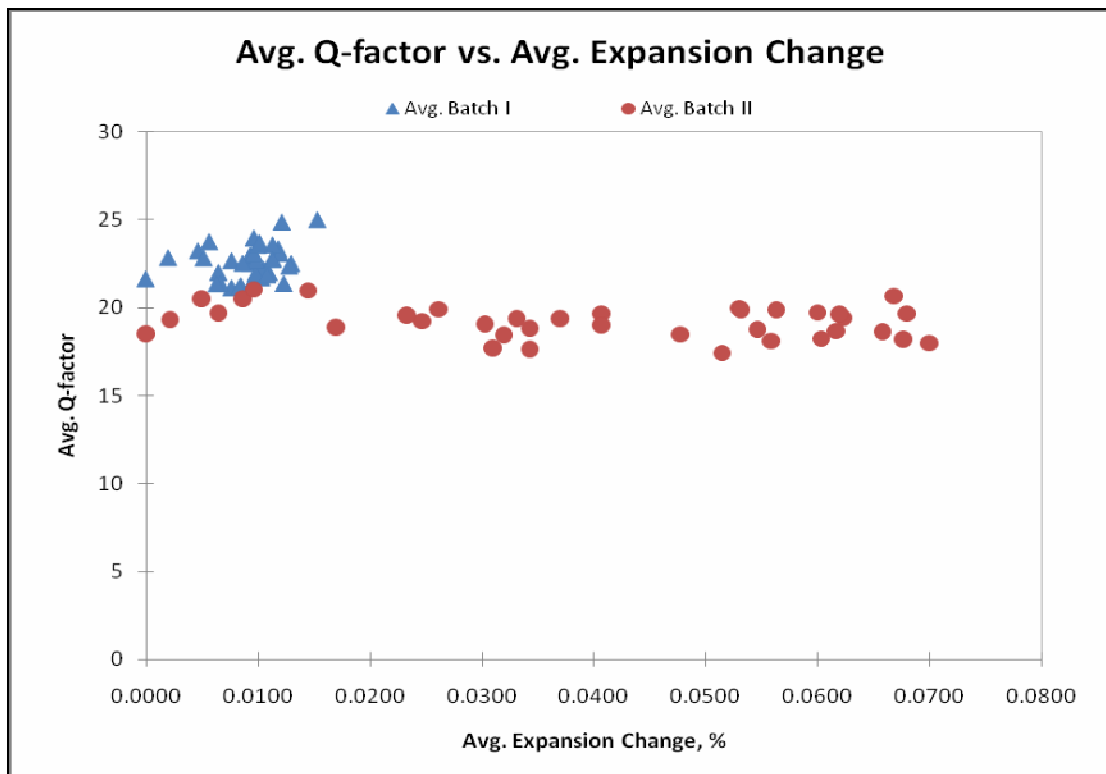


Figure 5.11: Q-factor and Expansion Change Correlation of Duggan Specimens

The fit of the linear regression model in the specimens from Batch I and Batch II was not found to be very strong. The coefficients of determination, R^2 , were 0.0852 and 0.0869, for Batch I and Batch II respectively. These coefficients suggest that the fit is weak and, therefore, the correlation is weak. The slope of the linear trend line represents the variation in Q-factor with varied expansion. Based on results of a

previous study (McMorris et al, 2007) it was expected that a decrease in expansion would be associated with an increase in Q-factor. Conversely, this was only the case for the specimens from Batch II as those from Batch I produced a positive slope revealing that a decrease in expansion was associated with a decrease in Q-factor. In fact, the Q-factors from Batch I seemed to increase over time instead of decrease as expected. El-Korchi et al (1989) suggest that one way the value of Q can increase is through the creation of a more dense material through increased or continued hydration of cement. El-Korchi et al (1989) concluded that continued cement hydration would decrease void space and hence decrease the damping and internal friction which would minimize the energy loss associated with the transfer of P-waves resulting in large Q parameter values. Thus, the increase in Q-factors found in this study could be due to the storage condition since the specimens were stored in limewater before subjecting them to the Duggan Cycle and throughout the entire period of the research study.

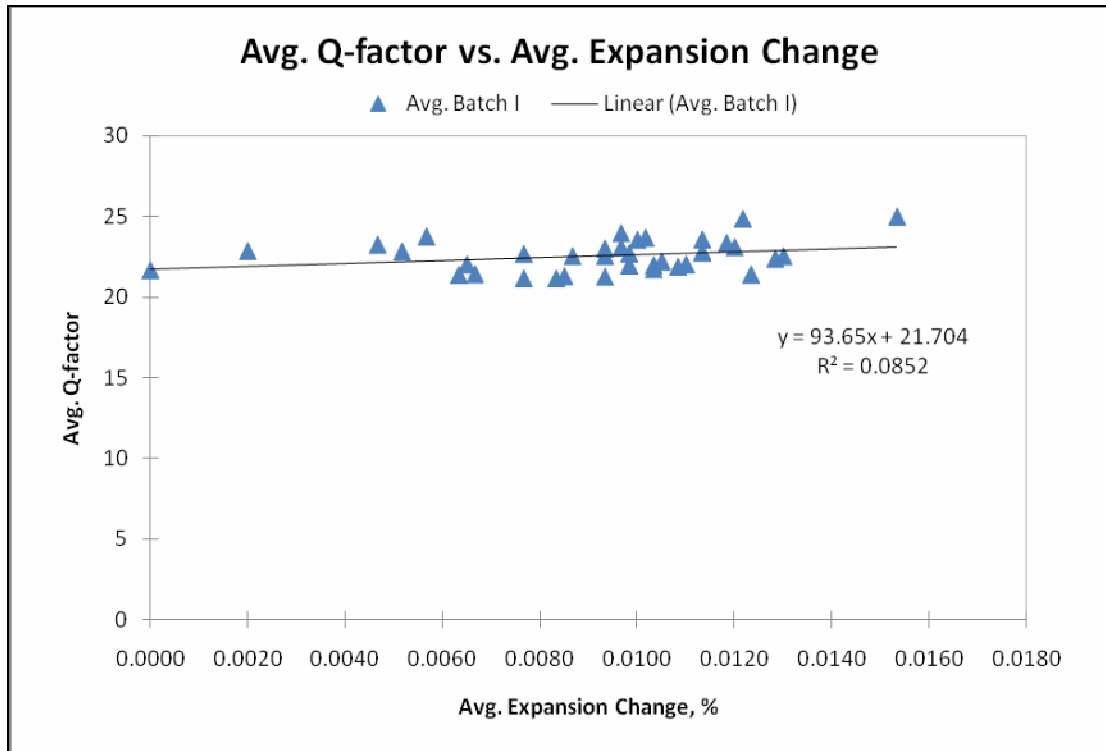


Figure 5.12: Q-factor and Expansion Change Correlation of Batch I (Duggan)

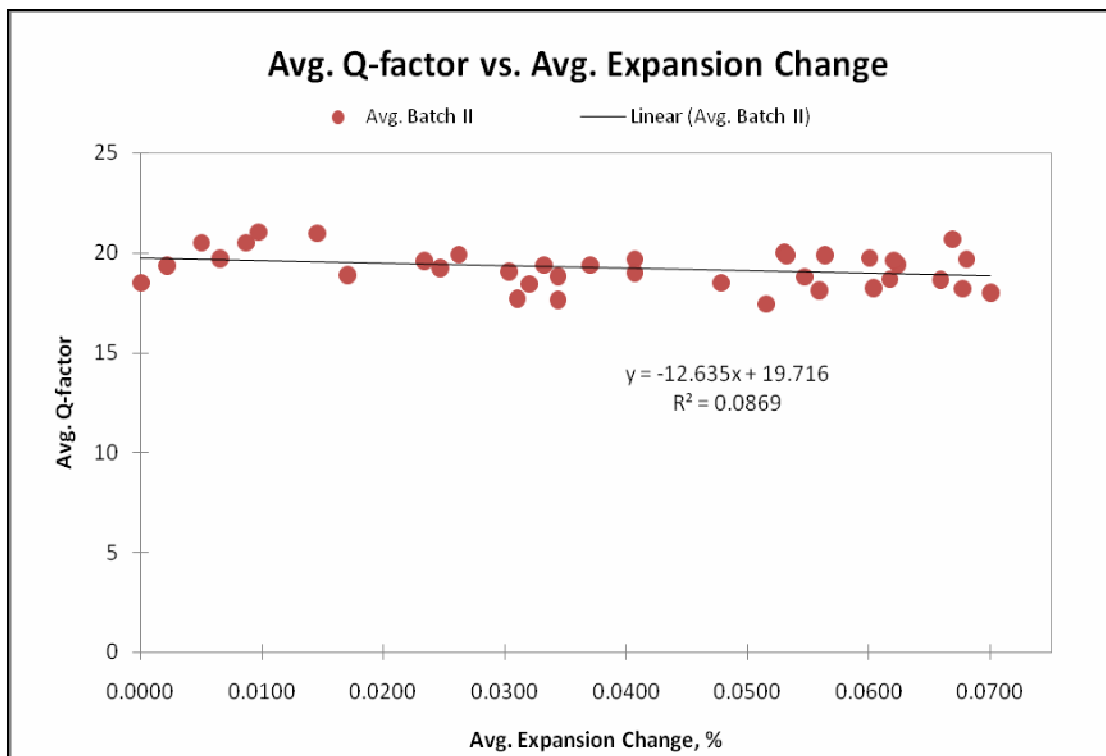


Figure 5.13: Q-factor and Expansion Change Correlation of Batch II (Duggan)

5.6.1.2 Weight Change Correlation

The second correlation sought from these specimens was one between the Q-factor values and the weight change experienced. Figure 5.14 shows the plot of the Q-factors obtained versus weight change measurements. As can be seen from the plot, the data from Batch I is not as widely spread as the data from Batch II. However, a linear regression analysis was performed on both batches and displayed by Figure 5.15 and Figure 5.16 to investigate possible correlations.

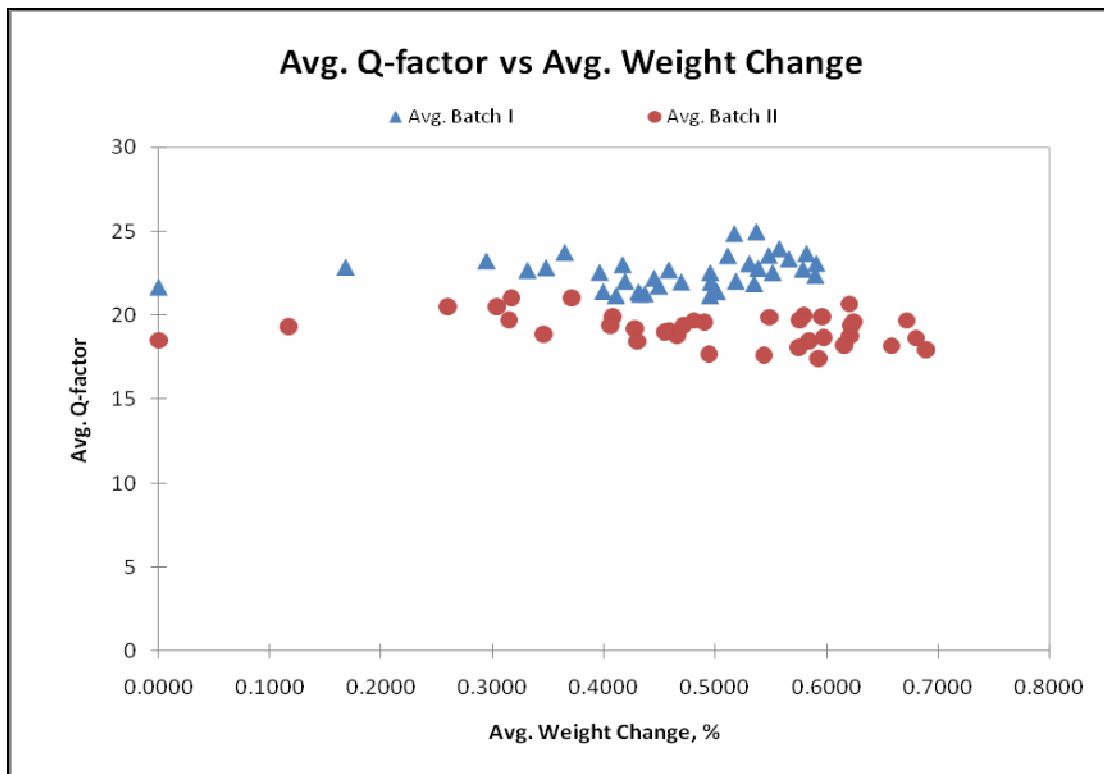


Figure 5.14: Q-factor and Weight Change Correlation of Duggan Specimens

The linear regression analyses revealed that the correlation of the specimens' Q-factors and weight change was weak. The linear regression model for Batch I was found to have a coefficient of determination (R^2) of 0.0603 which does not suggest a

very strong correlation. Batch II had a coefficient of determination of 0.0764 which also reveals a poor correlation. The slope of the linear trend line represents the variation in Q-factor with varied weight change. As expected based on the previous analysis of the correlation between Q-factor and expansion, the decrease in weight change of Batch I was accompanied with a decrease in Q-factors which resulted in a positive slope of the line.

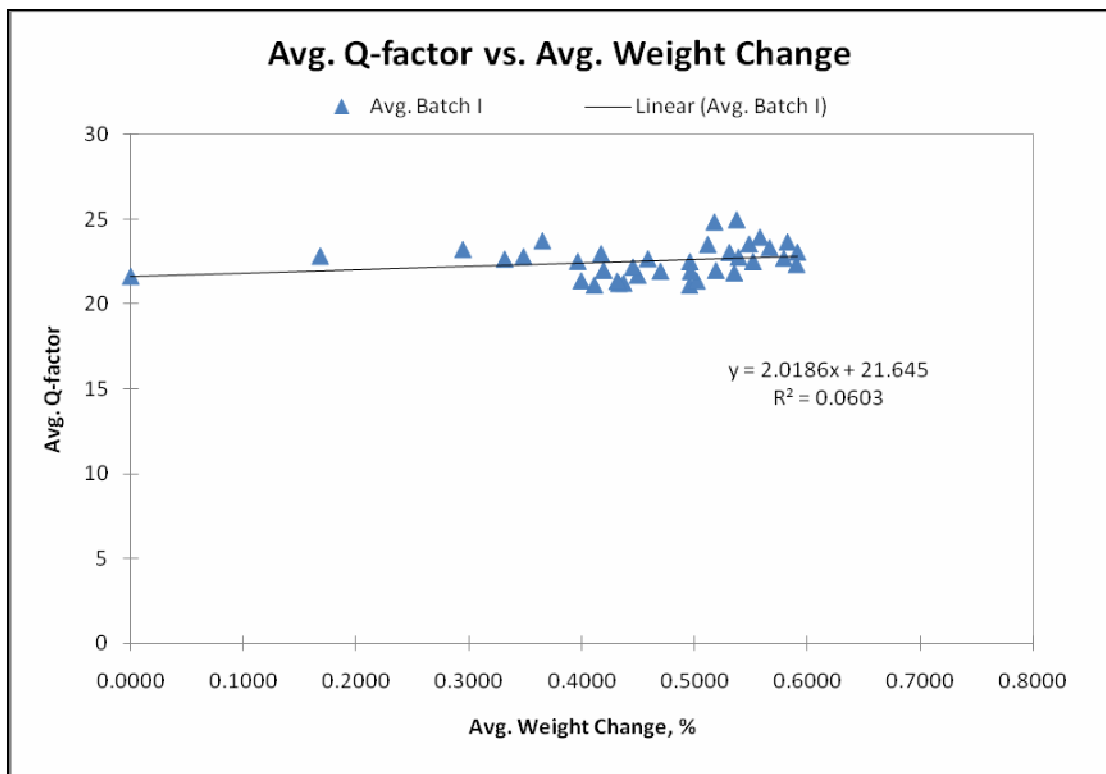


Figure 5.15: Q-factor and Weight Change Correlation of Batch I (Duggan)

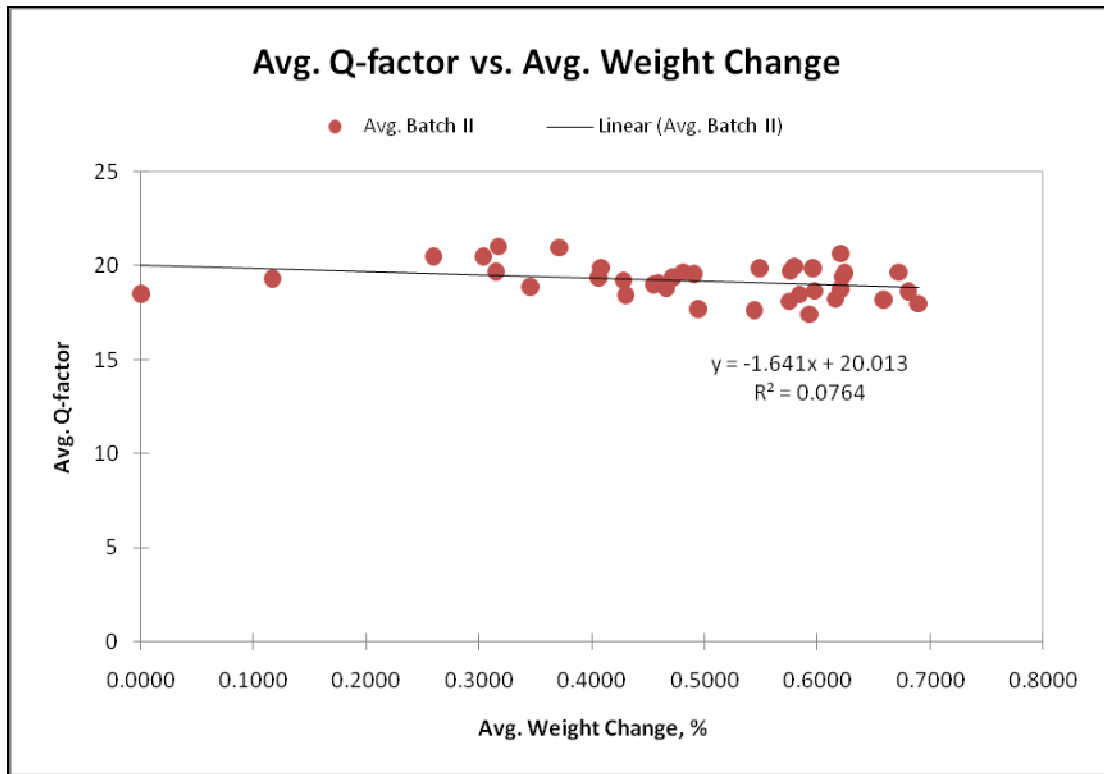


Figure 5.16: Q-factor and Weight Change Correlation of Batch II (Duggan)

5.6.1.3 Compression Strength Correlation

The third correlation sought of the specimens subjected to the Duggan Cycle was one between Q-factor values and compression strength of the concrete at different intervals. Figure 5.17 shows the correlation between Q-factors and compression strength of Batch I and Batch II. As mentioned earlier, the specimens from Batch II were significantly weaker than those from Batch I due to the deterioration caused by the addition of the potassium carbonate. In fact, the compression strength decreased at 150 days after the completion of the Duggan Cycle. For this reason, the last test data point from Batch II was omitted from the linear regression analysis performed.

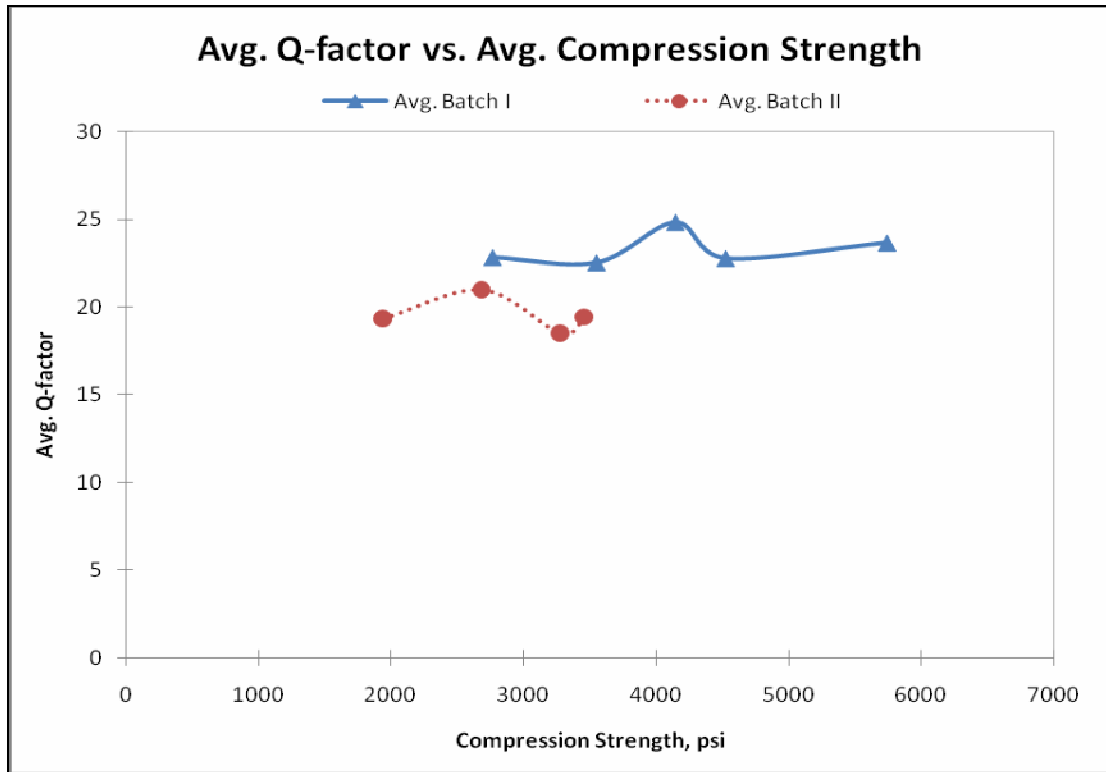


Figure 5.17: Q-factor and Compression Strength Correlation of Duggan Specimens

The regression analysis is shown by Figure 5.18 and Figure 5.19. The analyses revealed a poor correlation between Q-factors and compression strength by each batch. The coefficients of determination found were 0.1256 for Batch I and 0.0736 for Batch II. The slope of the linear trend line represents the variation in Q-factor with varied compression strength. As expected, Batch I revealed a positive slope as Q-factors from this batch increase over the five month period of the research study.

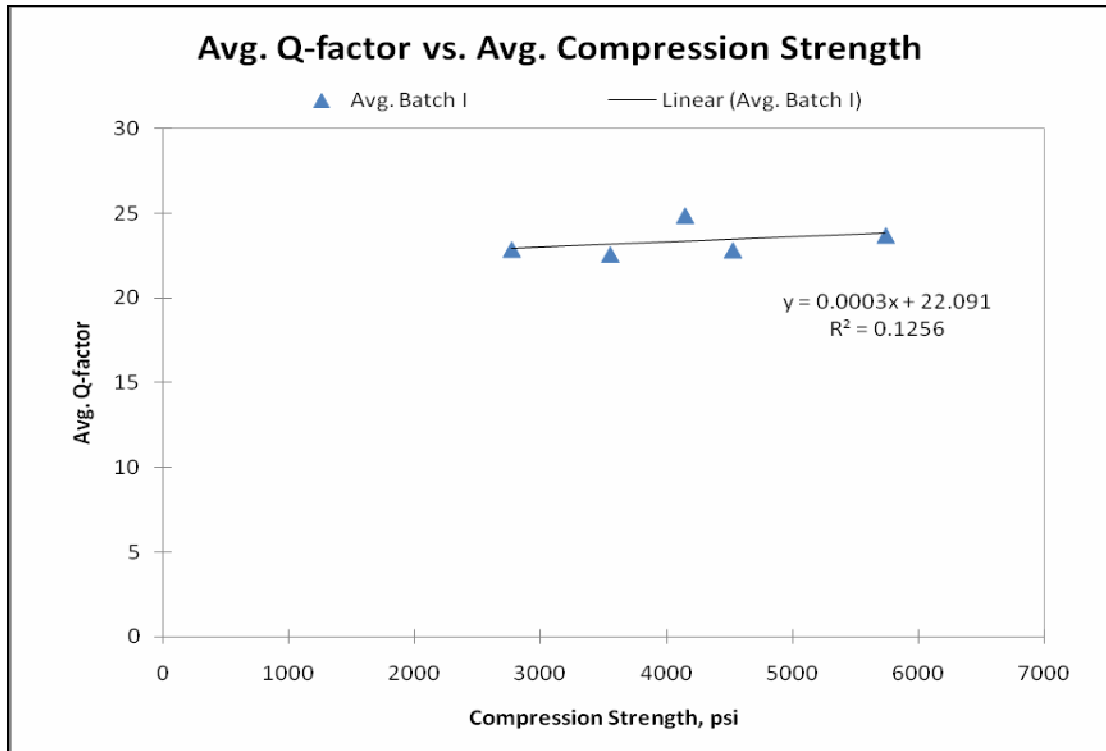


Figure 5.18: Q-factor and Compression Strength Correlation of Batch I (Duggan)

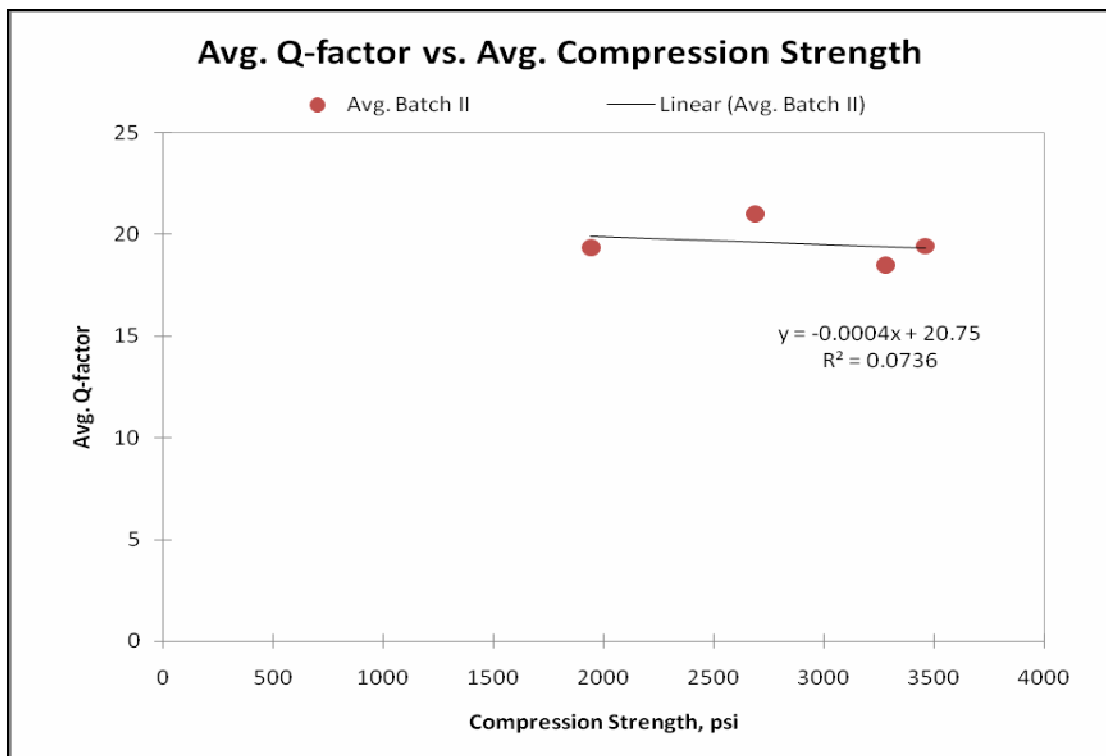


Figure 5.19: Q-factor and Compression Strength Correlation of Batch II (Duggan)

5.6.2 Environmental Chamber Freeze-Thaw Batch I and Batch II

5.6.2.1 Expansion Correlation

Since the specimens subjected to the Freeze-Thaw cycles in the Environmental Chamber were tested until failure or until data could no longer be obtained because of heavy deterioration, these specimens were expected to reveal stronger correlations. The correlation between expansion change and Q-factors was analyzed first. Figure 5.20 shows a plot of the average Q-factors obtained versus the expansion change observed by Batch I and Batch II. Seeing as a correlation between these two parameters was evident in both batches, a linear regression analysis was performed for each batch as shown by Figure 5.21 and Figure 5.22.

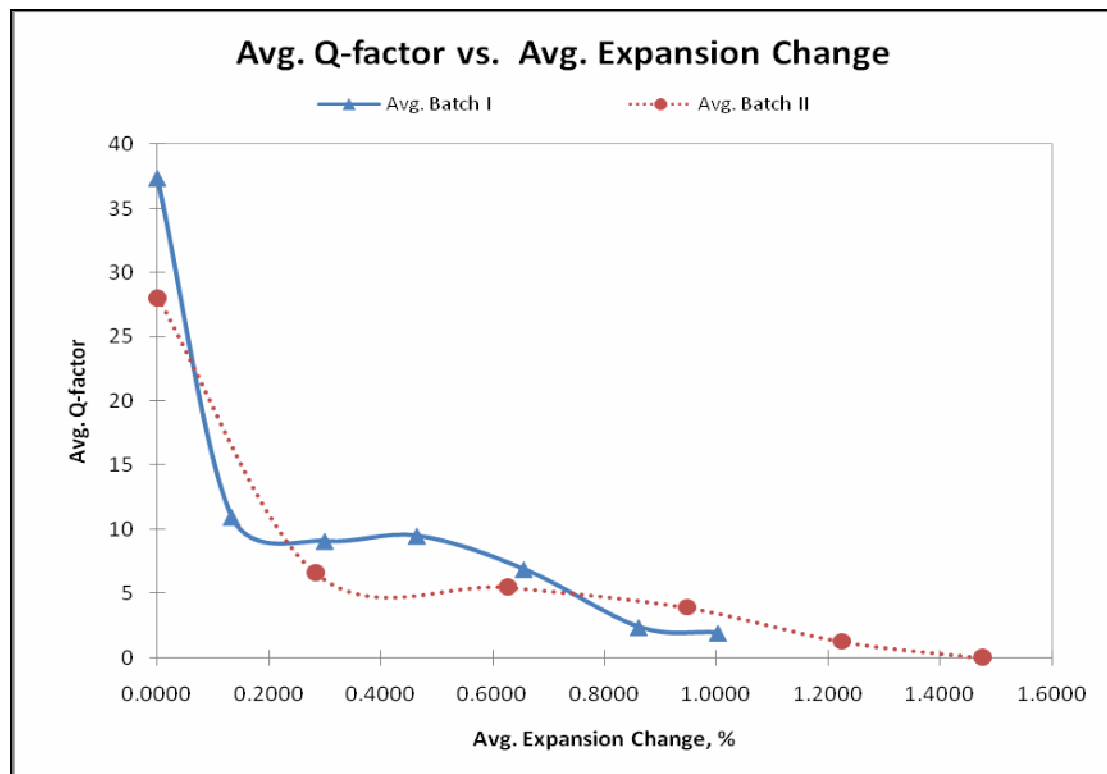


Figure 5.20: Q-factor and Expansion Change Correlation of Env. Chamber Specimens

The linear regression model of Batch I was found to have a coefficient of determination of 0.6074 which suggests the correlation is somewhat weak. The coefficient of determination of Batch II was 0.6703, which implies a stronger correlation than that of Batch I but a correlation that is nonetheless still somewhat weak. It is expected that if data had been obtained between fewer cycles, the correlation between these parameters might have been stronger; in this study measurements were only taken every ten cycles and a total of six to seven data measurements were gathered before failure. The slope of the linear trend line represents the variation in Q-factor with varied expansion, and, as was expected, a decrease in expansion was accompanied with an increase in Q-factors.

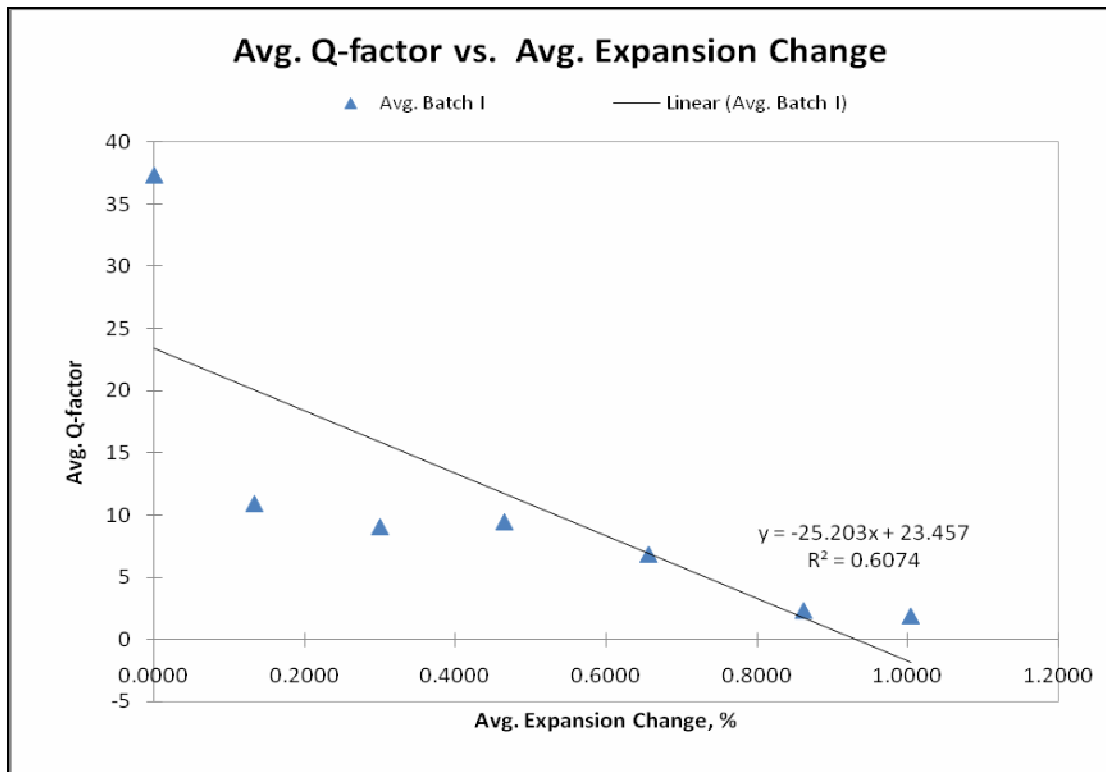


Figure 5.21: Q-factor and Expansion Change Correlation of Batch I (Env. Chamber)

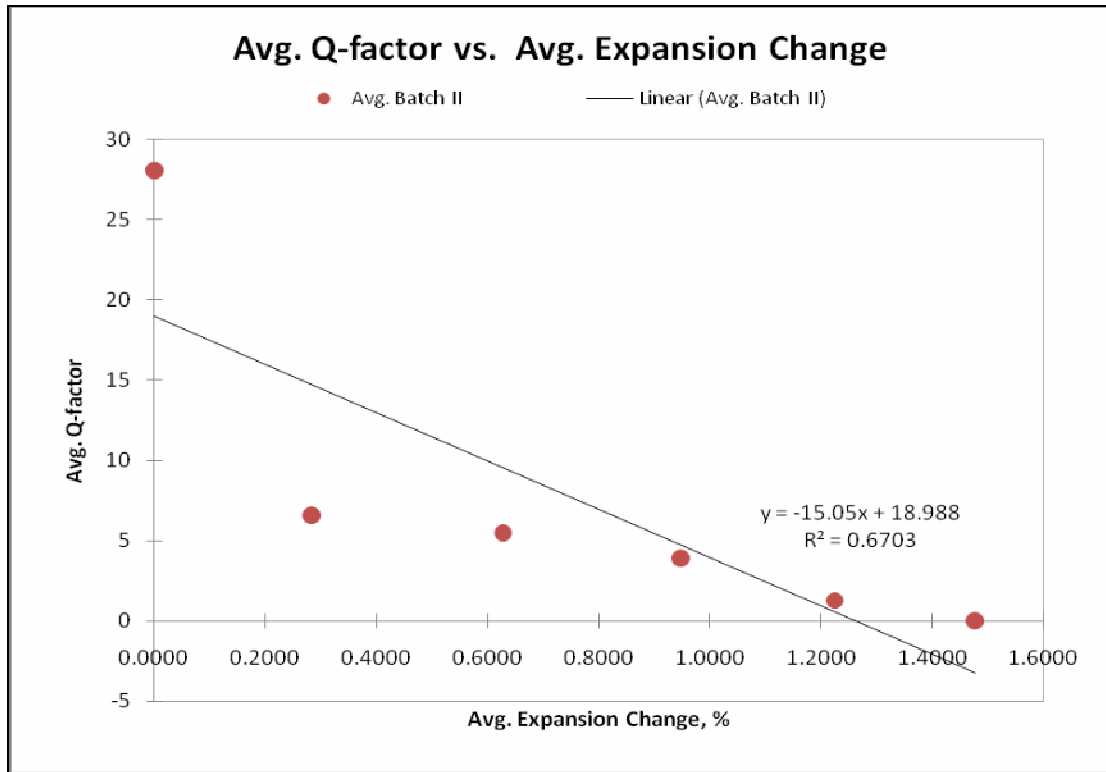


Figure 5.22: Q-factor and Expansion Change Correlation of Batch II (Env. Chamber)

5.6.2.2 Weight Change Correlation

The second correlation sought of the specimens subjected to the Freeze-Thaw cycles in the Environmental Chamber was one between Q-factors and weight change measurements. Figure 5.23 shows a plot of the Q-factors versus the weight change obtained from Batch I and Batch II. As it can be observed from the plot, a correlation between these two parameters exists. To further explore this, a linear regression analysis was performed for each batch.

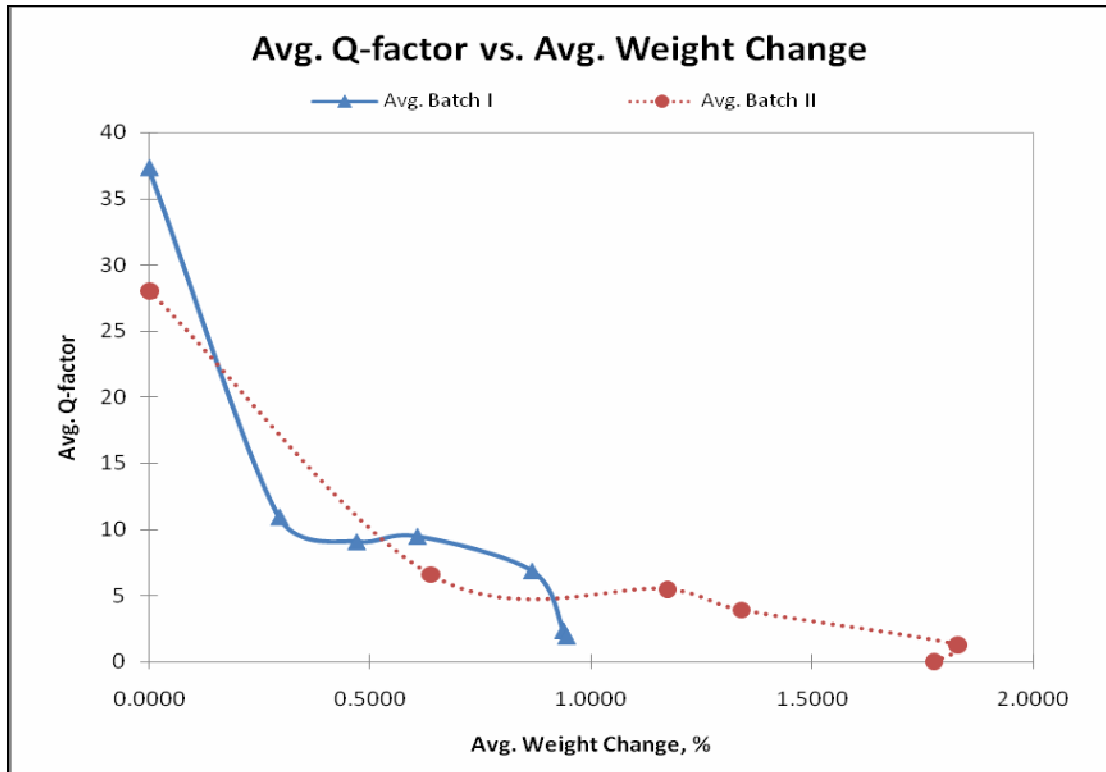


Figure 5.23: Q-factor and Weight Change Correlation of Env. Chamber Specimens

The linear regression analysis for each batch is displayed in Figure 5.24 and Figure 5.25. The fit of the linear regression model of Batch I was good as revealed by its coefficient of determination of 0.7613. However, Batch II showed to have an even stronger correlation since its coefficient of determination was 0.8138. Again, it is expected that the correlation between these two parameters could have been stronger if data had been taken between fewer cycles. The slope of the linear trend line represents the variation in Q-factor with varied weight change and, as was expected, a decrease in weight change was accompanied with an increase in Q-factor values.

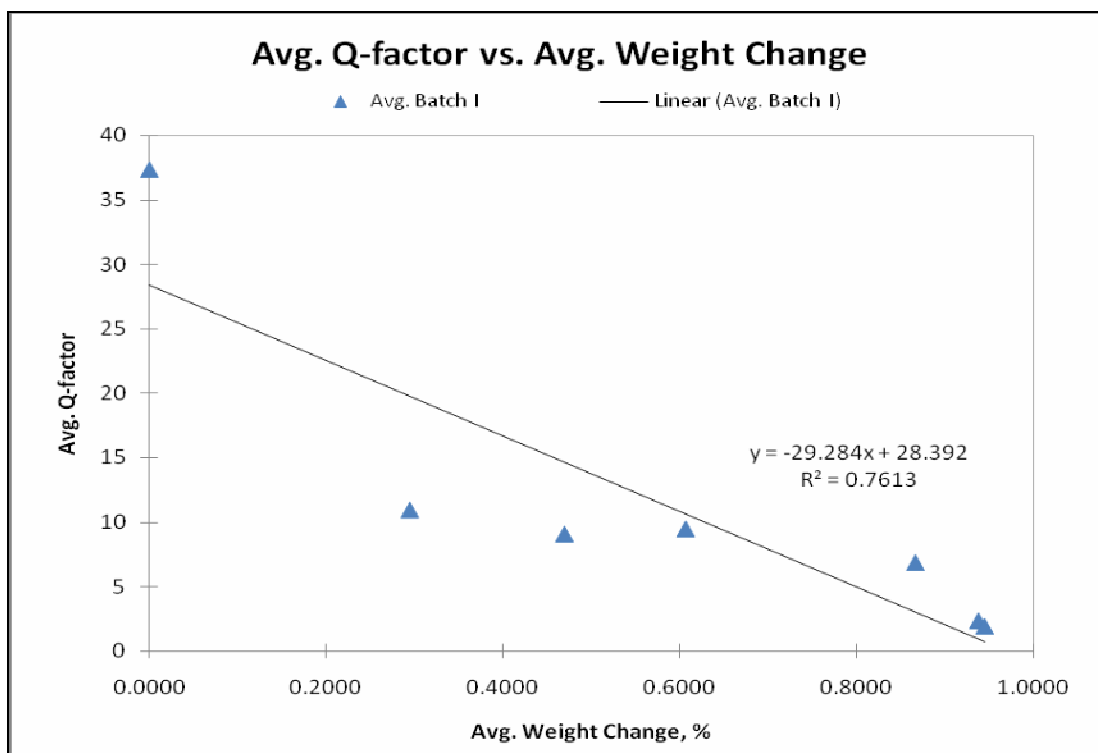


Figure 5.24: Q-factor and Weight Change Correlation of Batch I (Env. Chamber)

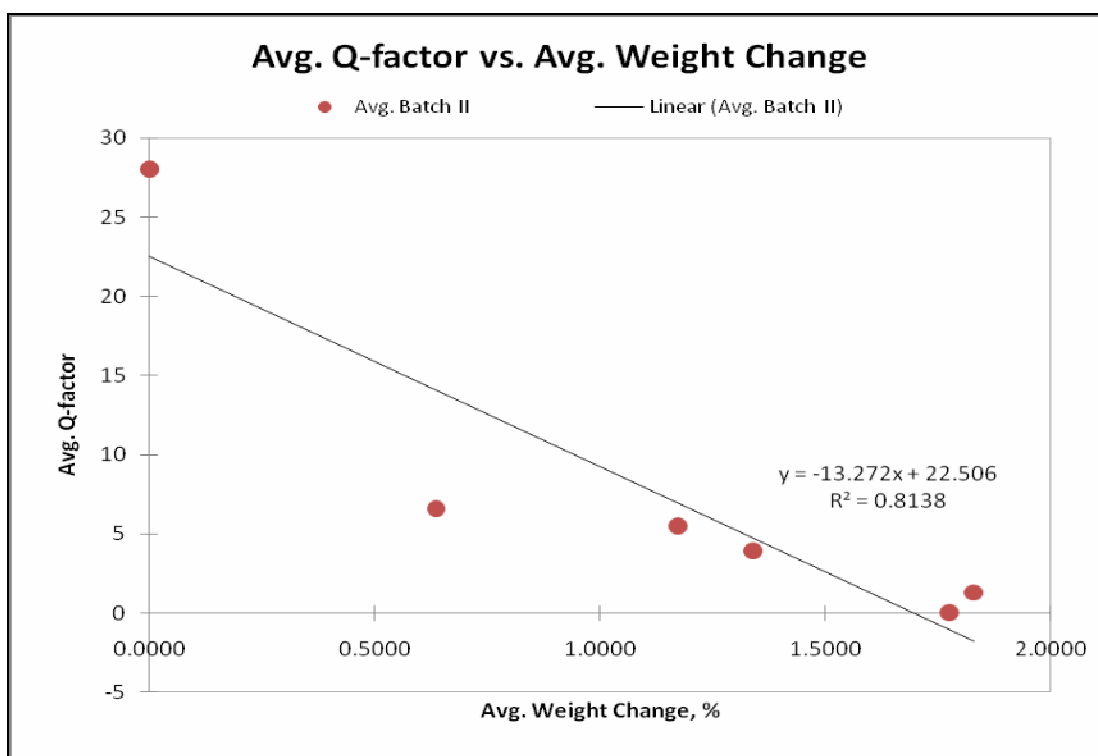


Figure 5.25: Q-factor and Weight Change Correlation of Batch II (Env. Chamber)

5.6.3 Cabinet Apparatus Freeze-Thaw Batch I and Batch II

5.6.3.1 Expansion Correlation

The specimens subjected to the Freeze-Thaw cycles in the Rapid Freeze-Thaw Cabinet apparatus also were tested until failure or until the data could no longer be obtained. Since data for these specimens was gathered between fewer cycles than the data from the specimens used in the Environmental Chamber, stronger correlations were expected. The correlation between Q-factors and expansion change was sought first. Figure 5.26 shows a plot of Q-factors obtained versus the expansion change experienced by Batch I and Batch II. Linear regression analysis was performed for each batch as shown in Figure 5.27 and Figure 5.28.

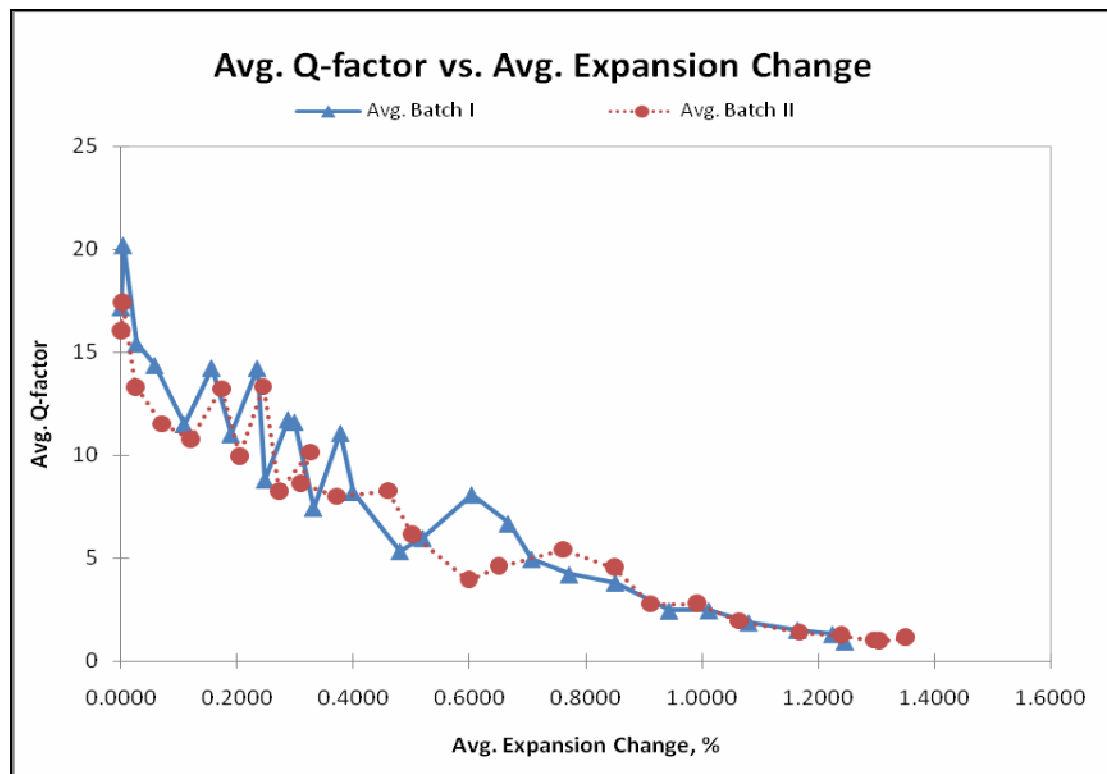


Figure 5.26: Q-factor and Exp. Change Correlation of F-T Cabinet Specimens

The linear regression model of Batch I was found to have a coefficient of determination of 0.8651 which suggests a strong correlation. The fit of the regression model was even stronger in Batch II since its coefficient of determination was 0.8819. The goodness of the fit of the linear model is probably due to the amount of data used in the analysis. The correlations found by these specimens were much stronger than the ones found by the specimens subjected to the Freeze-Thaw cycles in the Environmental Chamber where less data was analyzed. The slope of the linear trend line represents the variation in Q-factor with varied expansion, as expected a decrease in expansion was accompanied with an increase in Q-factors.

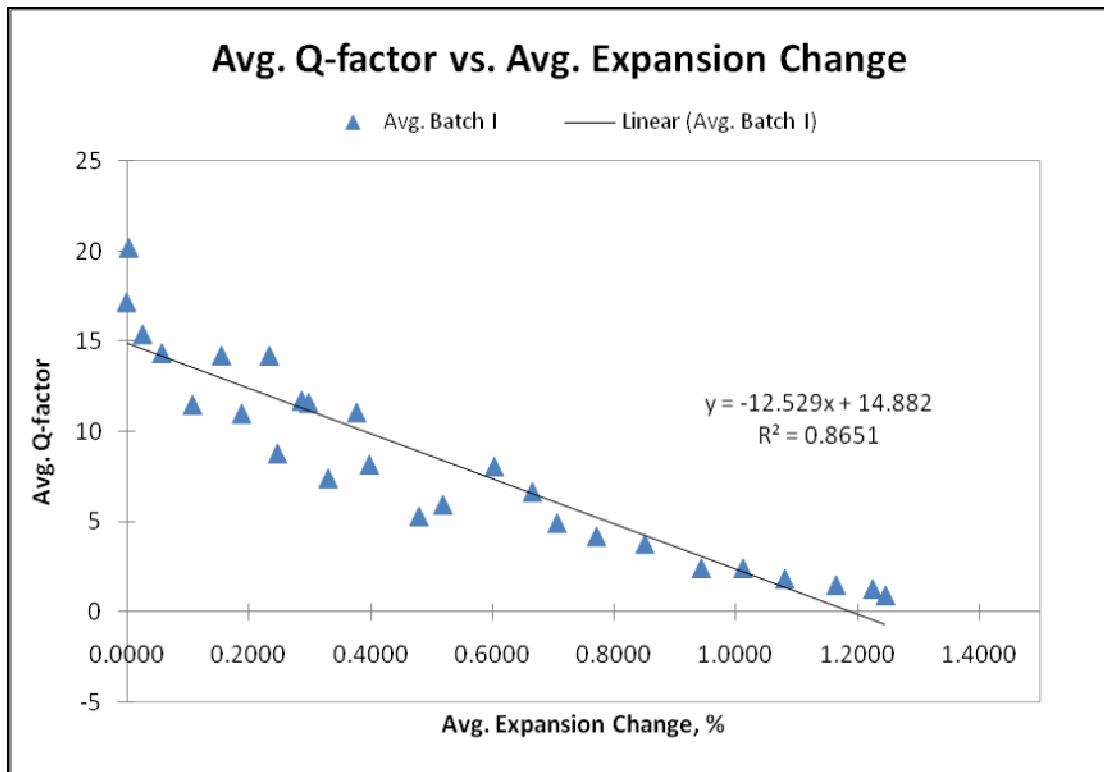


Figure 5.27: Q-factor and Expansion Change Correlation of Batch I (F-T Cabinet)

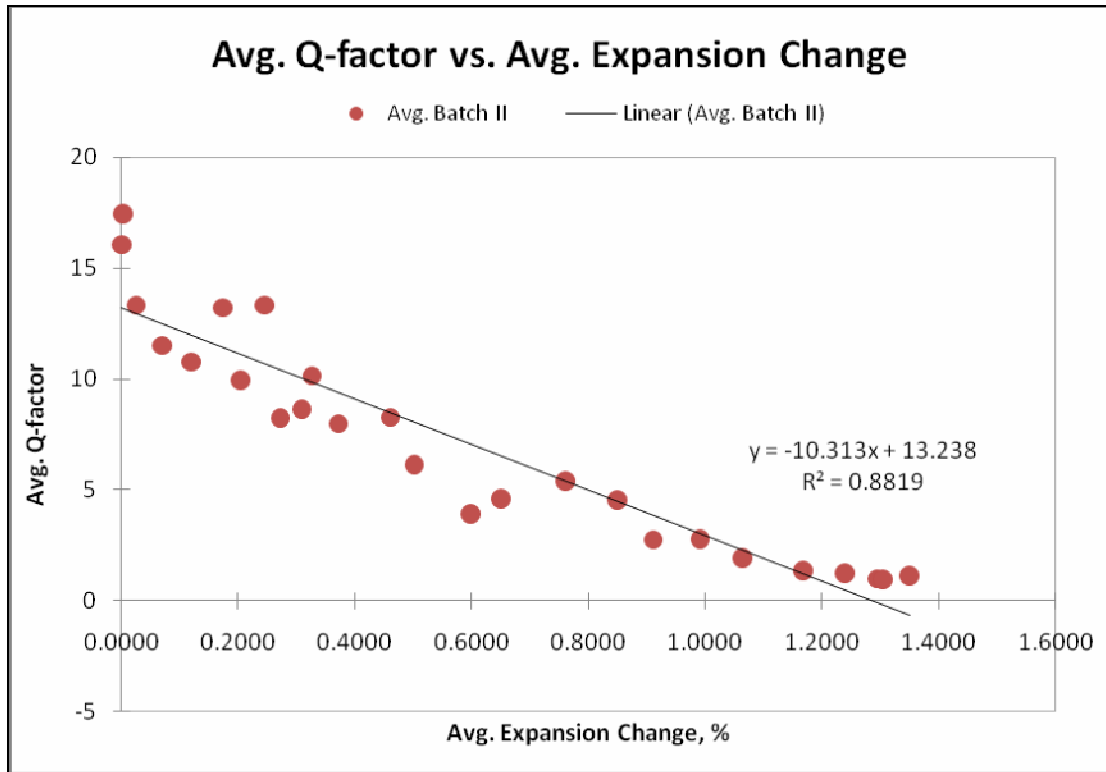


Figure 5.28: Q-factor and Expansion Change Correlation of Batch II (F-T Cabinet)

5.6.3.2 Weight Change Correlation

The second correlation sought of the specimens subjected to Freeze-Thaw cycles in the Rapid Freeze-Thaw Cabinet apparatus was one between Q-factors and the weight change experienced. Figure 5.29 shows the plot of Q-factors versus the weight change observed from the specimens of Batch I and Batch II. The plot reveals a possible correlation between these parameters, thus a linear regression analysis for each batch was performed as shown by Figure 5.30 and Figure 5.31.

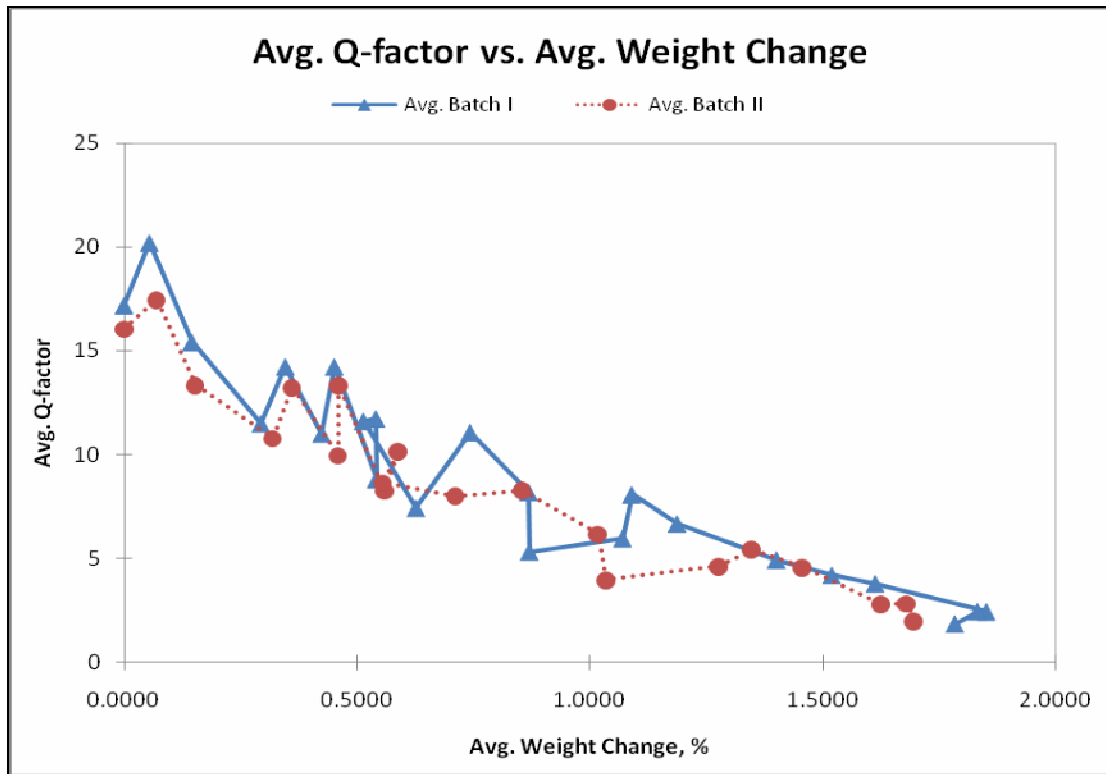


Figure 5.29: Q-factor and Weight Change Correlation of F-T Cabinet Specimens

The linear regression analyses revealed strong correlations between these two parameters in both batches. The fit of the linear model of Batch I was found to be strong due to its high coefficient of determination of 0.8598. Batch II suggested an even stronger correlation since the coefficient determination for this batch was found to be 0.8870. These correlations were considerably stronger than the ones found in the specimens subjected to the Freeze-Thaw cycles in the Environmental Chamber. The slope of the linear trend line represents the variation in Q-factor with varied weight change, as expected a decrease in weight change was accompanied with an increase in Q-factors.

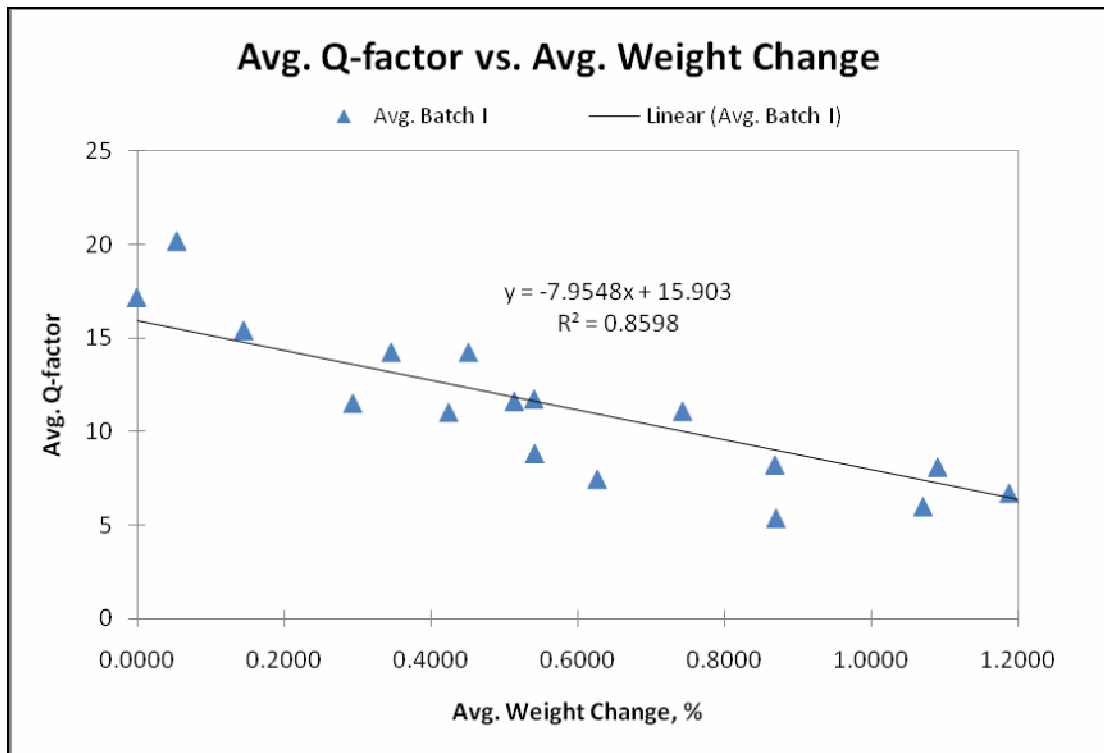


Figure 5.30: Q-factor and Weight Change Correlation of Batch I (F-T Cabinet)

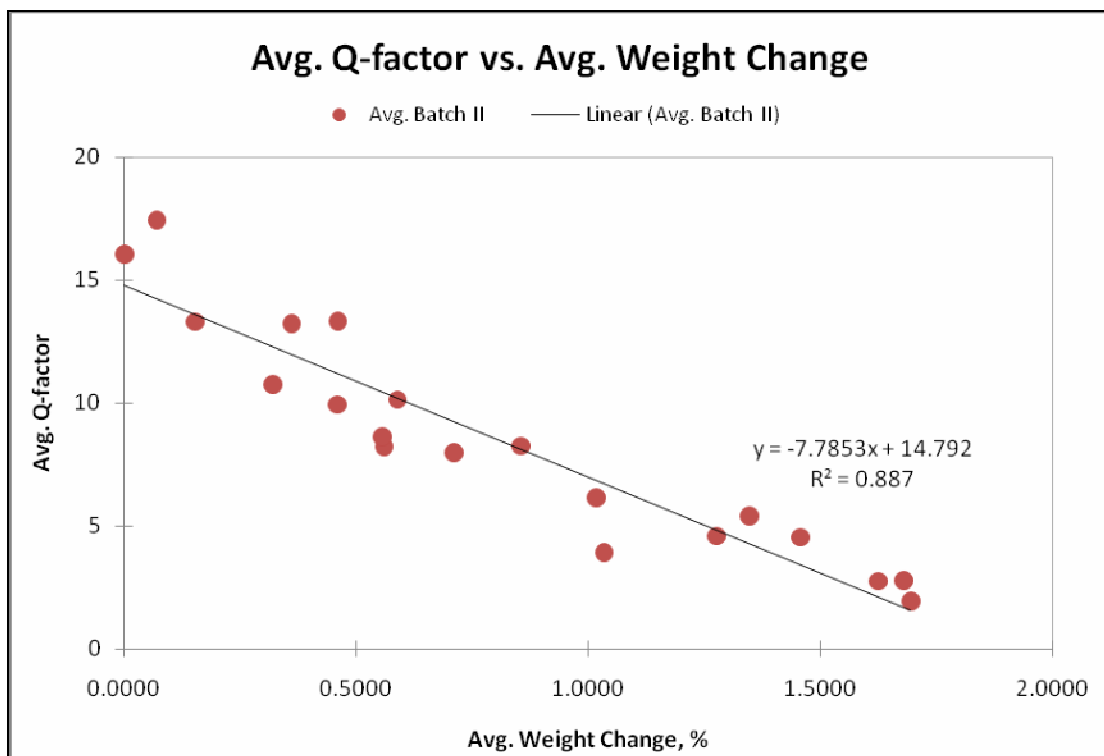


Figure 5.31: Q-factor and Weight Change Correlation of Batch II (F-T Cabinet)

5.7 Discussion of Results

It is evident from the results that adding potassium carbonate accelerated deterioration caused by DEF and ASR in the specimens from Batch II resulting in greater expansion in those specimens subjected to the UMD Modified Duggan Cycle, Freeze-Thaw cycles in the Environmental Chamber, and those in the Rapid Freeze-Thaw Cabinet apparatus. However, the deterioration was not well assessed by the weight change measurements. The weight change measurements from Batch I and Batch II were very similar in those specimens subjected to the Duggan Cycle and the Freeze-Thaw cycles in the Rapid Freeze-Thaw Cabinet apparatus. Nonetheless, there was a significant difference between the weight change measurements of Batch I and Batch II in the specimens subjected to the Freeze-Thaw cycles in the Environmental Chamber.

The deterioration due to DEF and ASR was evident from the Q-factor values obtained from all the specimens. A previous research project concluded that micro-cracking causes damping which in turn causes the free vibrations to decrease in amplitude as a function of time. Thus, as micro-cracking occurs, damping increases due to the pumping action that takes place as cracks open and close during the vibration cycle. As viscous damping increases with deterioration, the Q-factor values decrease (McMorris et al, 2007). This was evident from the results of this study since the Q-factors obtained from Batch II were much lower than those of Batch I. Additionally, deterioration was evident by the compression strength results of the specimens subjected to the Duggan Cycle as Batch II showed a decrease in compressive strength at 150 days of the completion of the heating regime.

As can be seen from Table 5.2 below, the specimens subjected to the Duggan Cycle did not show strong correlations. This was probably because these specimens did not deteriorate due to DEF and ASR as much in the five month period as the specimens subjected to Freeze-Thaw cycles. It is expected that results over a longer period of time will confirm stronger correlation between Q-factors and expansion and agree with observations made by a previous research study (McMorris et al, 2007). In that study, specimens were observed over a period of two years in which deterioration in the form of internal cracking caused by DEF and ASR caused the response spectrum to be less smooth and produced a significant decrease in Q-factor values.

The specimens subjected to the Freeze-Thaw cycles experienced heavy deterioration. The specimens in the Environmental Chamber revealed somewhat weak correlations between Q-factors and expansion and weight change parameters. However, it is expected that if data had been gathered between fewer cycles the correlations may have been stronger. The strongest correlations found were in the specimens subjected to the Freeze-Thaw cycles in the Rapid Freeze-Thaw Cabinet apparatus. The data from these specimens was gathered between fewer cycles than the data gathered from the specimens used in the Environmental Chamber.

It was observed that for each deteriorating method the correlations were always stronger, except for the compression strength correlations, in the specimens from Batch II than the correlations from Batch I. This suggests that further deterioration due to DEF and ASR took place in the specimens with the added potassium carbonate.

Table 5.2: Summary of Coefficients of Determination (R^2)

	Batch I	Batch II
Duggan Cycle		
Q-factor vs. Expansion Change	0.0852	0.0869
Q-factor vs. Weight Change	0.0603	0.0764
Q-factor vs. Compression Strength	0.1256	0.0736
Environmental Chamber: Freeze-Thaw		
Q-factor vs. Expansion Change	0.6074	0.6703
Q-factor vs. Weight Change	0.7613	0.8138
F-T Cabinet Apparatus: Freeze-Thaw		
Q-factor vs. Expansion Change	0.8651	0.8819
Q-factor vs. Weight Change	0.8598	0.8870

Chapter 6: Summary and Conclusions

6.1 Summary

The main objective of this research study was to find correlations between Q-factors and other parameters in deteriorated concrete. In addition, the effect of adding potassium carbonate to accelerate deterioration through the growth of ettringite was also investigated. The deteriorating methods included the UMD Modified Duggan Cycle and two sets of Freeze-Thaw cycles. The first set was done in an Environmental Chamber, and the second set in a Rapid Freeze-Thaw Cabinet apparatus. The project was conducted with two batches of concrete specimens prepared in the laboratory. One batch was used as control (Batch I), while the other one contained additional potassium carbonate (Batch II). A total of 12 prisms and 14 cylinders were used for each batch. In each batch, six prisms were used for the Duggan Cycle, three were used in the Environmental Chamber, and three were used in the Rapid Freeze-Thaw Cabinet apparatus. All the specimens used for the Duggan Cycle were steam-cured, while those used for the Freeze-Thaw cycles were cured at room temperature.

The specimens subjected to the Duggan Cycle were tested for expansion, weight change and Q-factor change through impact-echo testing every three to five days after the Duggan Cycle for approximately five months. The specimens subjected to the Freeze-Thaw cycles in the Environmental Chamber were tested for these measurements every ten cycles until Q-factors could no longer be attained. Those specimens used in the Rapid Freeze-Thaw Cabinet apparatus were tested every three cycles for the first 30 cycles and every five cycles until Q-factors could no longer be

obtained. Compression strength tests were carried out on specimens subjected to the Duggan Cycle. These compression tests were performed at 7, 30, 90, 120, and 150 days after the completion of the heating regime. A summary of the results found in this study are summarized in Table 6.1, Table 6.2, and Table 6.3.

Table 6.1: Summary of Measurements of the Duggan Specimens

Duggan Cycle Specimens	Batch I	Batch II
Max. Expansion Change	0.0153% at day 90	0.0700% at day 150
Max. Weight Change	0.5913% at day 128	0.6893% at day 150
Max. Compression Strength	5739 psi at day 150	3461 psi at day 120

Table 6.2: Summary of Measurements of the first set of Freeze-Thaw Specimens

Environmental Chamber	Batch I	Batch II
Max. Number of Cycles Endured	60 cycles	50 cycles
Max. Expansion Change	1.0037% at 60 cycles	1.4760% at 50 cycles
Max. Weight Change	0.9453% at 60 cycles	1.8306% at 40 cycles

Table 6.3: Summary of Measurements of the second set of Freeze-Thaw Specimens

F-T Cabinet Apparatus	Batch I	Batch II
Max. Number of Cycles Endured	105 cycles	100 cycles
Max. Expansion Change	1.2455% at 105 cycles	1.3500% at 100 cycles
Max. Weight Change	1.8518% at 80 cycles	1.6959% at 75 cycles

6.2 Conclusions

The following conclusions were reached based on the analysis of the results found in this research study:

- The addition of potassium carbonate accelerated deterioration in concrete prisms causing an increase in expansion of specimens subjected to the Duggan Cycle. However, the weight changes of these specimens were not significantly affected since both batches revealed similar weight changes.
- The concrete cylinders with added potassium carbonate subjected to the Duggan Cycle experienced a 10% decrease in compression strength at 150 days, while the control specimens experienced a 27% increase, suggesting that the potassium accelerated deterioration in the concrete.
- The specimens with added potassium carbonate subjected to the Freeze-Thaw cycles in the Environmental Chamber experienced a significant increase in expansion and weight change when compared to the control set. Both batches of the specimens used in the Rapid Freeze-Thaw Cabinet apparatus also experienced somewhat similar expansion and weight changes.
- Deterioration due to DEF and ASR caused by the potassium carbonate resulted in a decrease of Q-factor values of all the specimens when compared to the control sets.
- Specimens subjected to the Duggan Cycle revealed the weakest correlation between Q-factors versus expansion and weight changes. The correlation between Q-factors and compression strength was also very weak. The weakness of these correlations was probably because these specimens did not deteriorate as much as the ones used in the Freeze-Thaw cycles. Further research should be performed to investigate this observation over a long-term period (> five months).

- The specimens subjected to Freeze-Thaw cycles in the Environmental Chamber revealed stronger correlations between Q-factors versus expansion and weight change than the Duggan specimens. However, it is expected that these correlations might have been even stronger if data was gathered between fewer cycles (< ten cycles).
- The specimens used in the Rapid Freeze-Thaw Cabinet apparatus revealed stronger correlations between Q-factors versus expansion and weight change as compared with the other specimens subjected to freeze-thaw cycles. Data from these specimens was gathered between fewer cycles than the ones in the Environmental Chamber.
- This research study found that the most deteriorated specimens always revealed the strongest correlations, thus indicating that to obtain stronger correlations specimens should be analyzed until heavy deterioration is reached. Since the specimens subjected to the heat cycle did not deteriorate much over the period of this study, it is recommended that such specimens be subjected to additional heating cycles or be examined for a period longer than five months.

Appendix

Plots of Individual Specimens

Expansion Plots

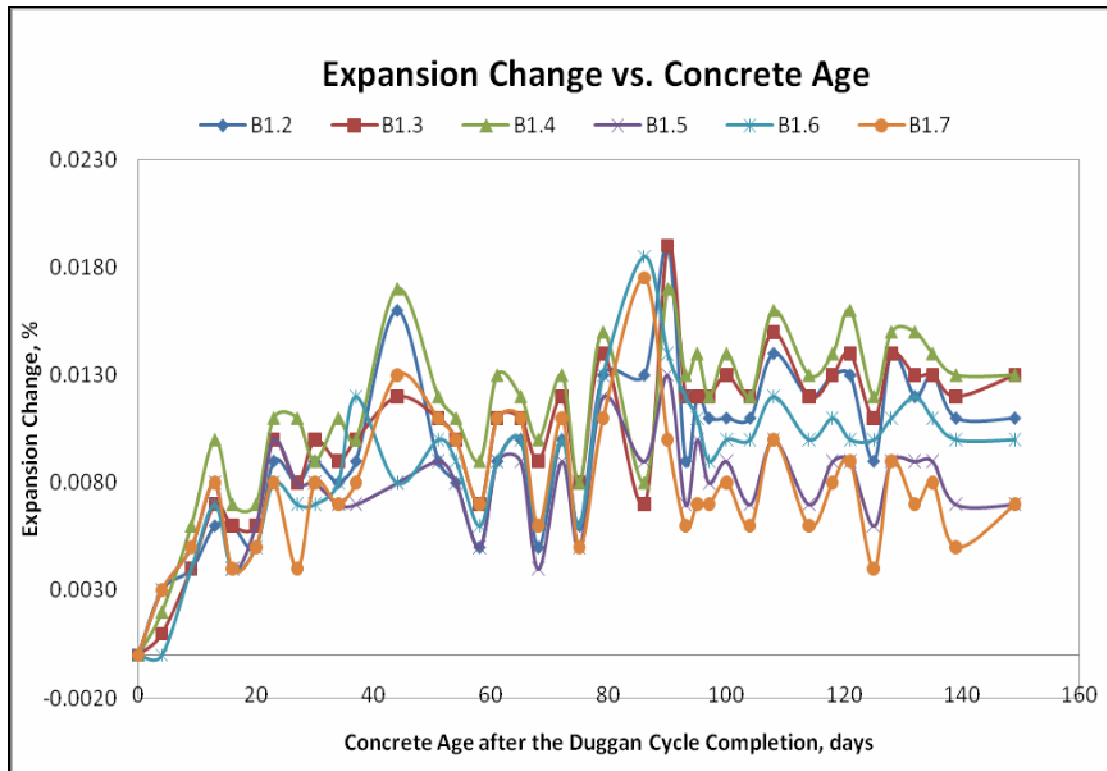


Figure A.1: Duggan Batch I- Expansion vs. Concrete Age after Duggan Cycle

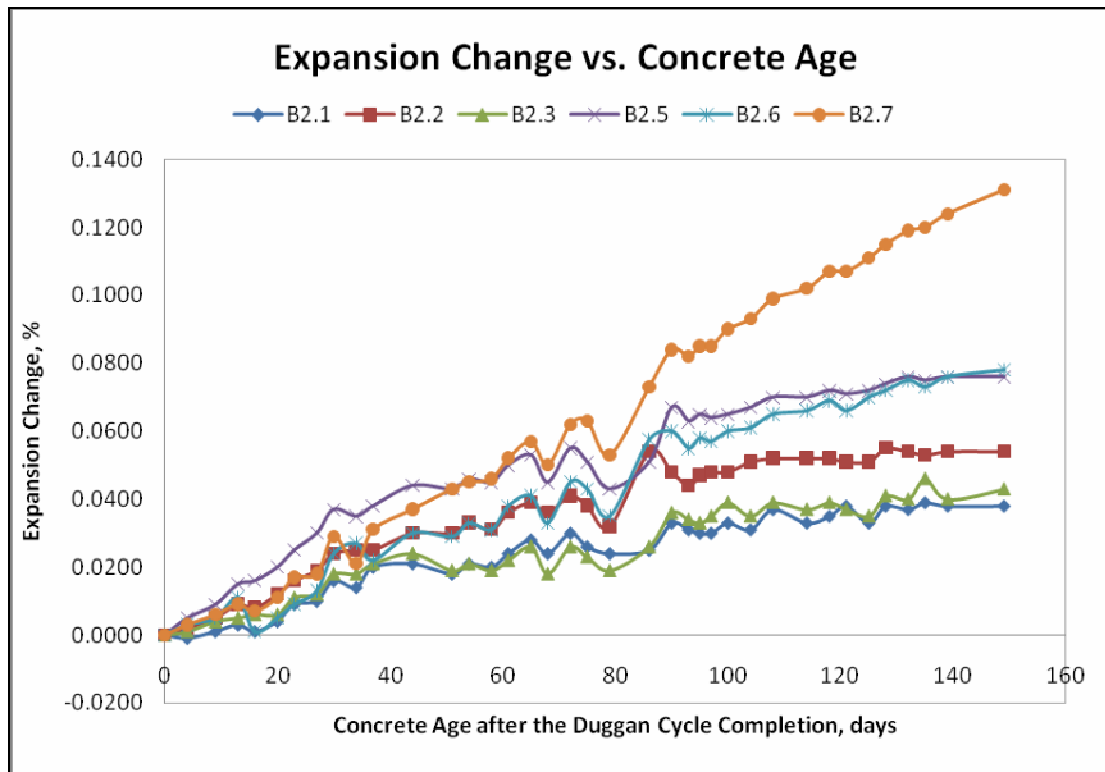


Figure A.2: Duggan Batch II- Expansion vs. Concrete Age after Duggan Cycle

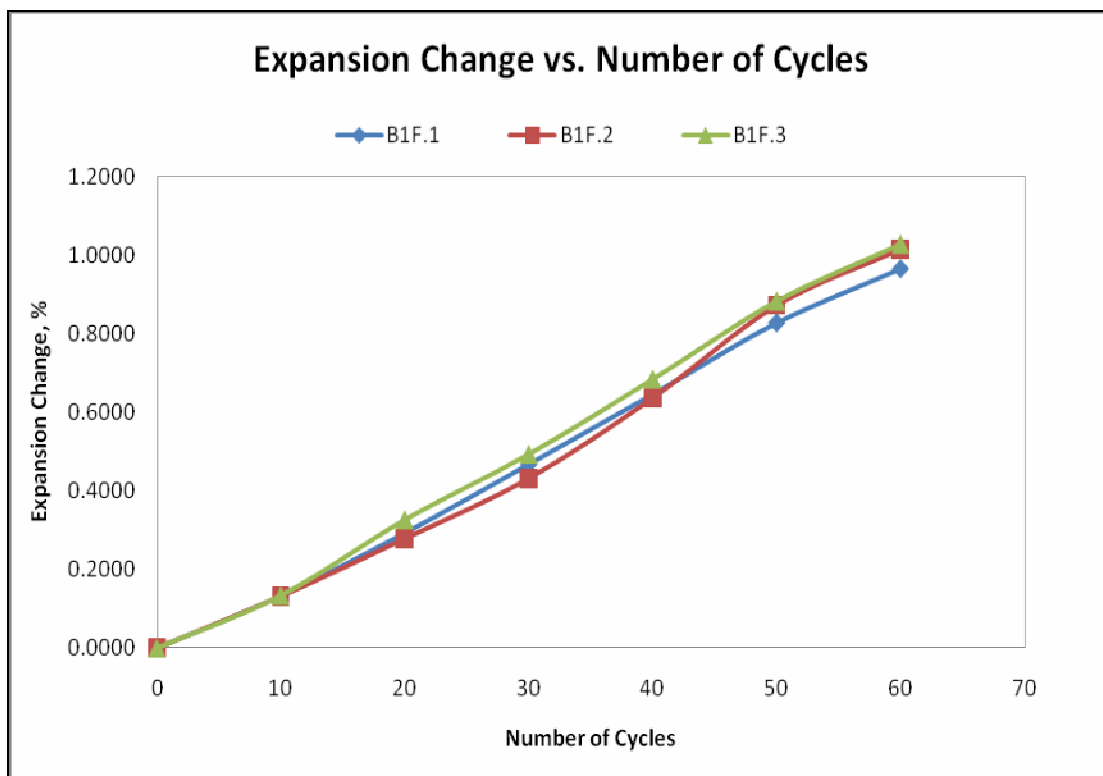


Figure A.3: Environmental Chamber Batch I- Expansion vs. Number of Cycles

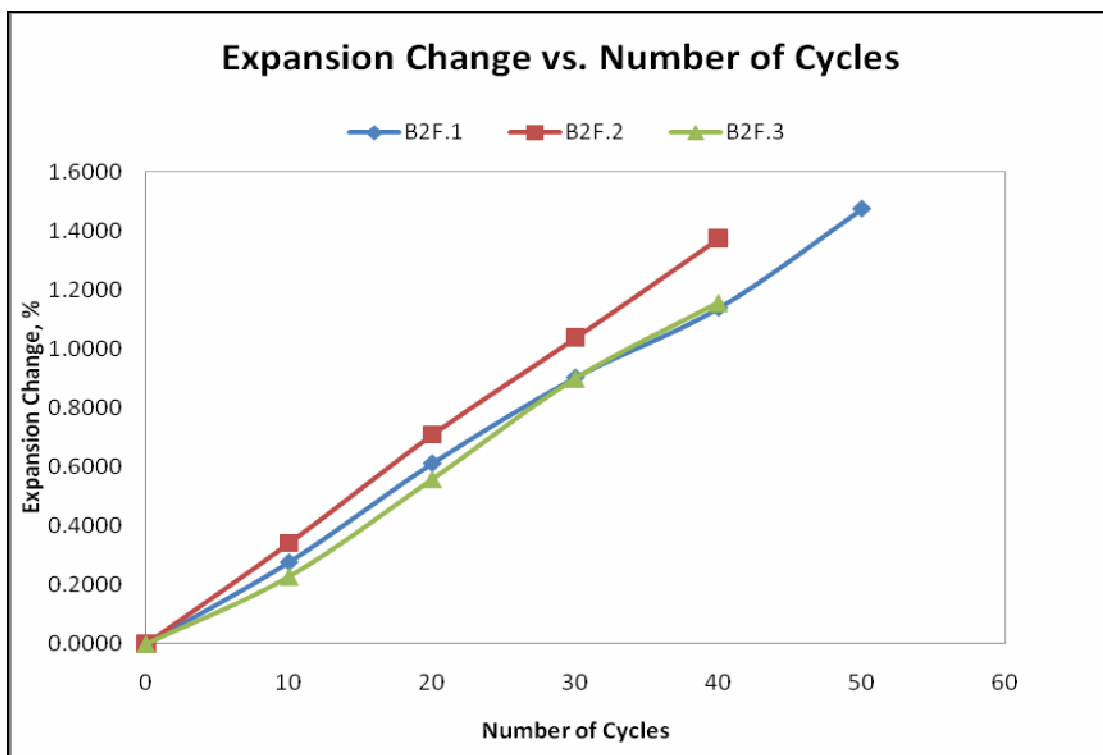


Figure A.4: Environmental Chamber Batch II- Expansion vs. Number of Cycles

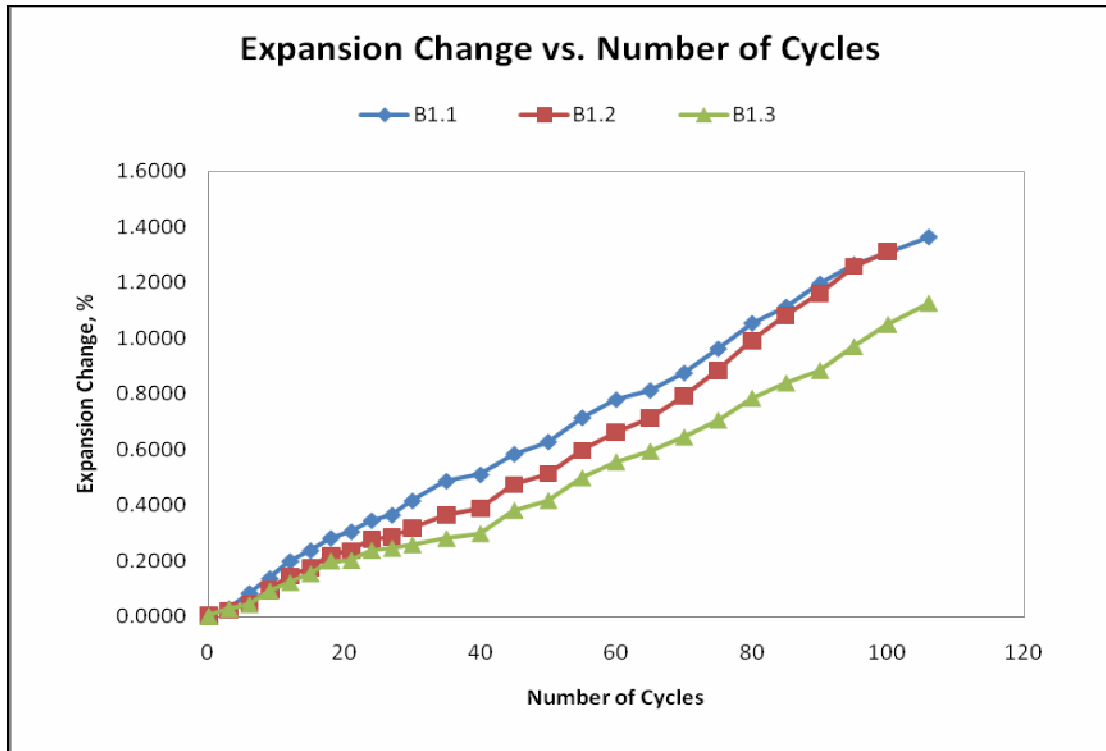


Figure A.5: Freeze-Thaw Cabinet Batch I- Expansion vs. Number of Cycles

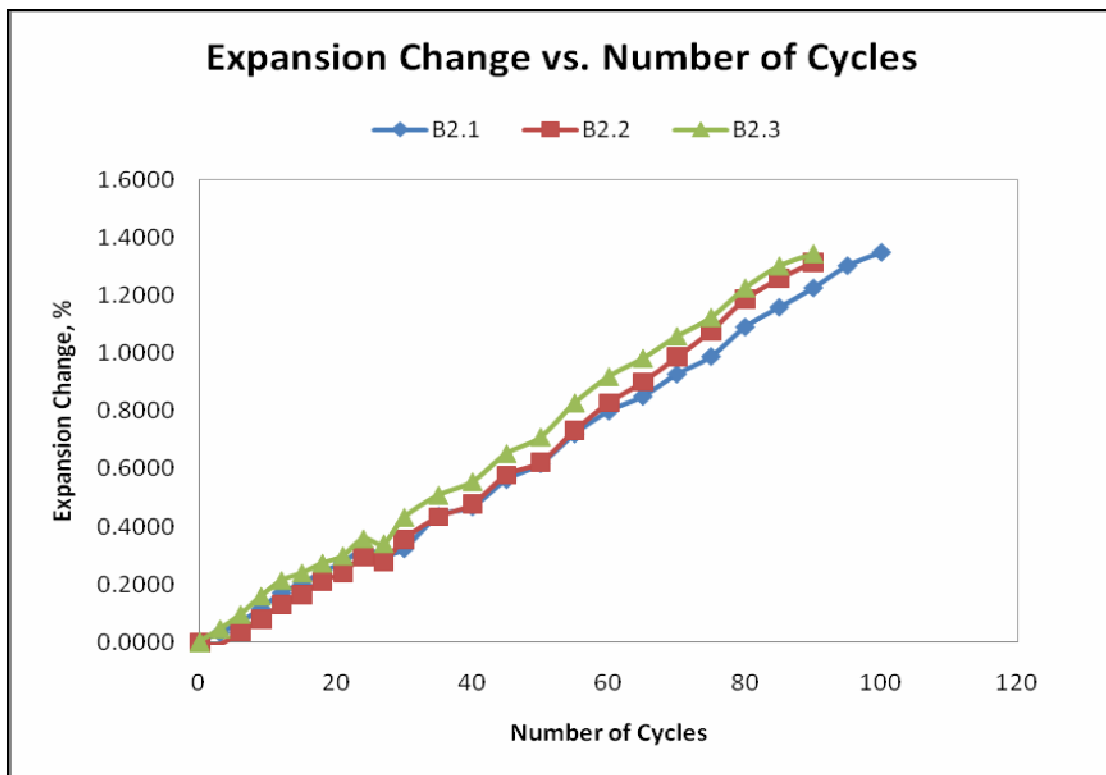


Figure A.6: Freeze-Thaw Cabinet Batch II- Expansion vs. Number of Cycles

Weight Plots

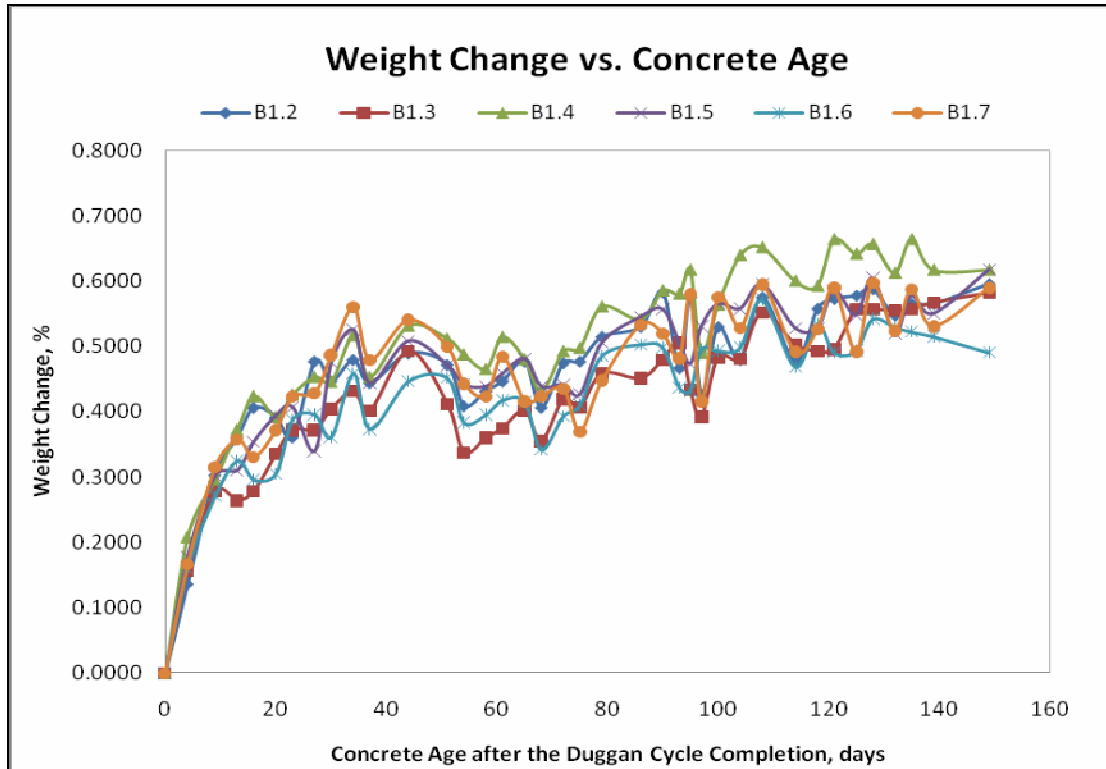


Figure A.7: Duggan Batch I- Weight Change vs. Concrete Age after Duggan Cycle

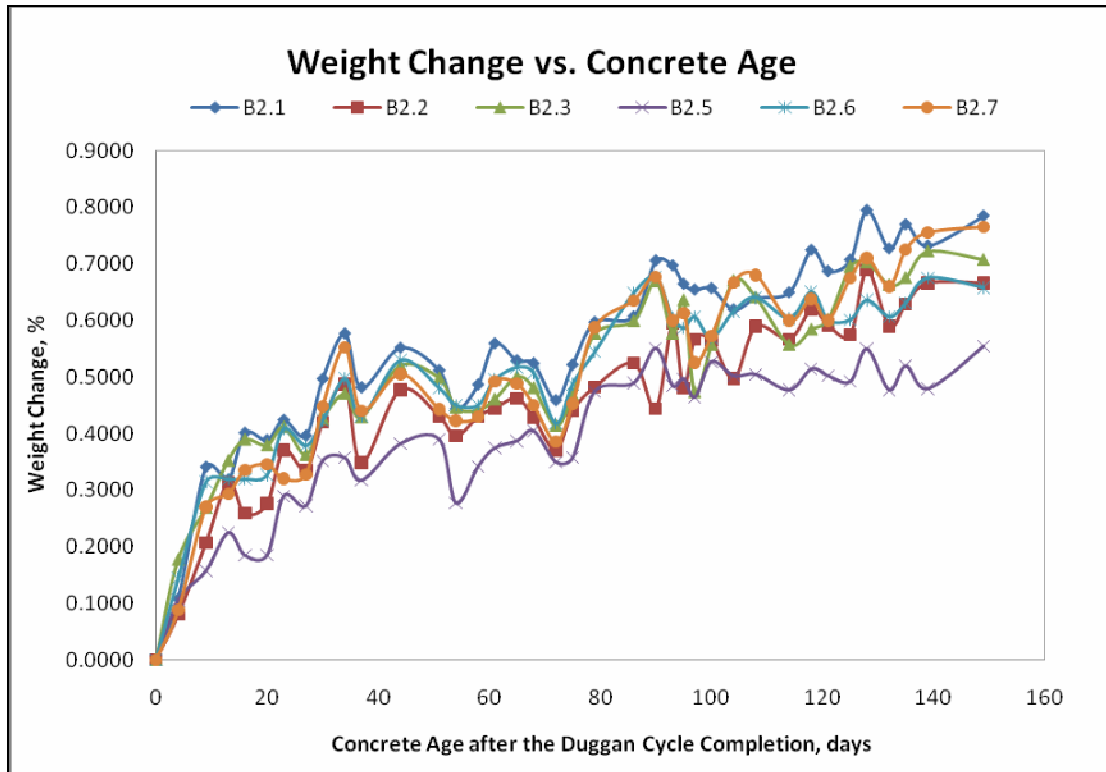


Figure A.8: Duggan Batch II- Weight Change vs. Concrete Age after Duggan Cycle

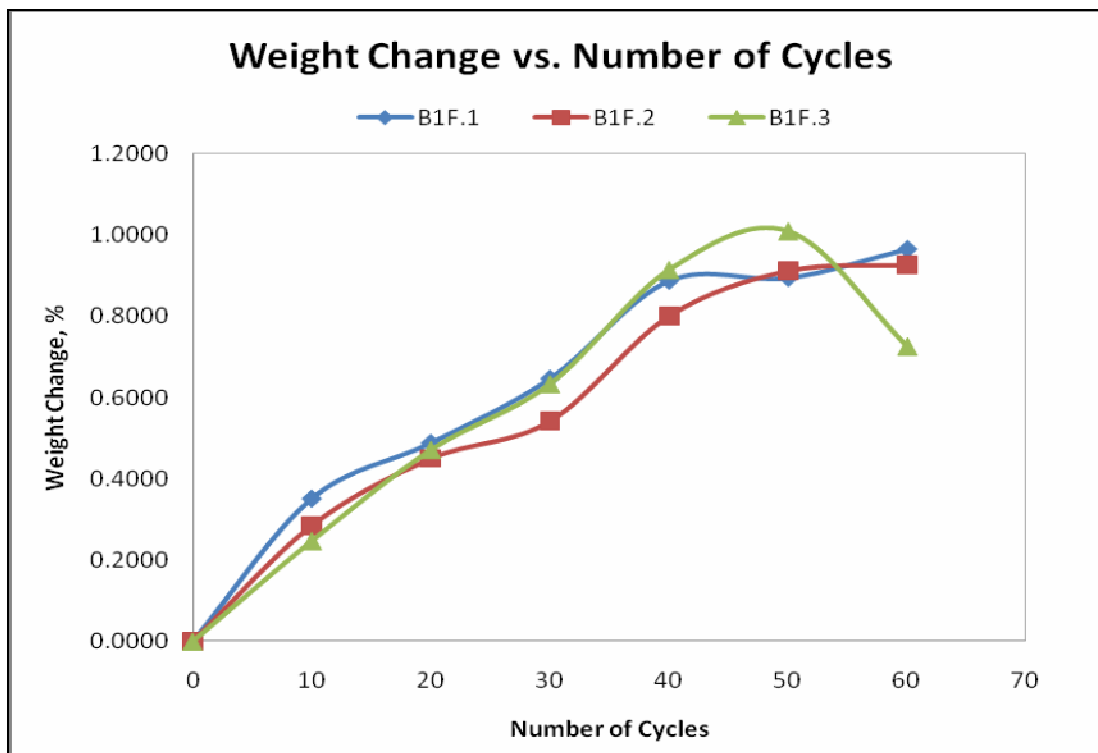


Figure A.9: Environmental Chamber Batch I- Weight Change vs. Number of Cycles

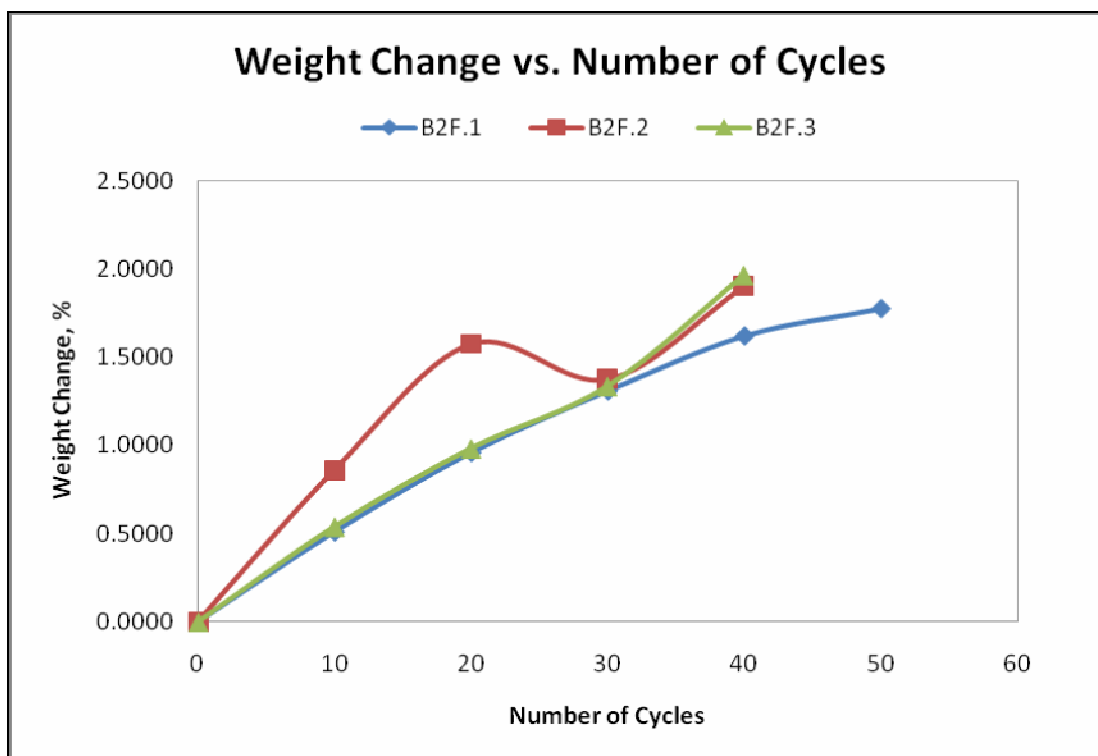


Figure A.10: Environmental Chamber Batch II-Weight Change vs. Number of Cycles

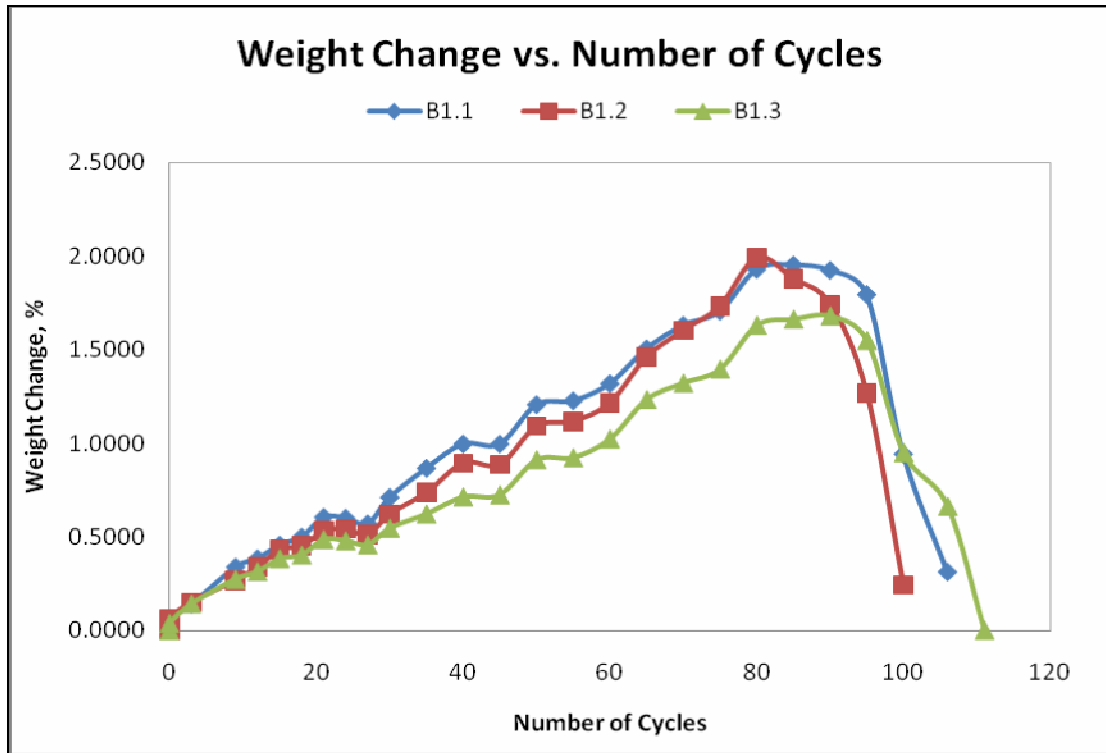


Figure A.11: Freeze-Thaw Cabinet Batch I- Weight Change vs. Number of Cycles

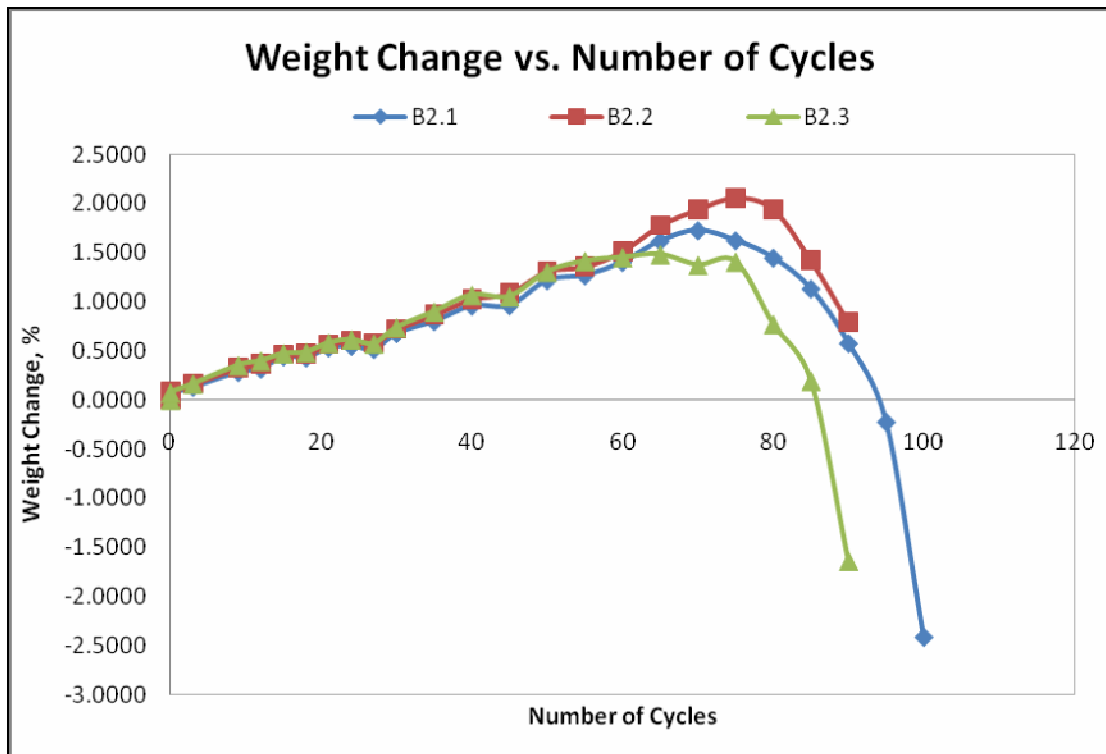


Figure A.12: Freeze-Thaw Cabinet Batch II- Weight Change vs. Number of Cycles

Bibliography

- Abraham, O., Leonard, C., Cote, P., & Piwakowski B. (2000). *Time Frequency Analysis of Impact-Echo Signals: Numerical Modeling and Experimental Validation*. ACI Materials Journal, Vol. 97, No. 6, 2000, pp. 645-657.
- Amde, A.M., Ceary, M., and Livingston, R. (2003). *Measurement of Expansion Associated with DEF*. 106th Annual Meeting & Exposition of the American Ceramic Society, Indianapolis.
- Amde, A.M., Ceary, M., and Livingston, R.A., (2005). *Investigation of Maryland Bridges for DEF and ASR*. ICACS Int. Conf., Chennai, India, January, 809-816 (**Keynote Paper**).
- Amde, A. M., and Livingston, R. A. (2004). *UMD/FHWA Studies on Delayed Ettringite Formation*. International Conference on Advances in Concrete and Construction (ICACC2004), Hyderabad, India, December 2004, 424-434 (**Keynote Paper**).
- Amde, A.M., Livingston, R.L., and Azzam, A. (2003). *Influence of Alkali Content and Development of Accelerated Test Method for Delayed Ettringite Formation*. Proceedings of the International Innovative World of Concrete Conference. Pune, India.
- American Concrete Institute International. (1999). *Ettringite—The Sometimes Host of Destruction* (SP-177). Farmington Hills, Michigan.
- Azzam, A. E. (2002). *Delayed Ettringite Formation, the Influence of Aggregate Types, Curing Conditions, Exposure Conditions, Alkali Content, Fly Ash, and Mix Water Conditioner (MWC)*. Ph.D. Thesis, University of Maryland, College Park, USA.
- Bungey, J. H., & Millard S. G. (1996). *Testing of Concrete in Structures*. London: Chapman & Hall.
- Carino, N.J. (2001). *The Impact-Echo Method: An Overview*. Proceedings of the 2001 Structures Congress & Exposition, May 21-23, Washington, D. C. American Society of Civil Engineers, 18 p.
- Ceesay, J. (2004). *The Influence of Exposure Conditions on Delayed Ettringite Formation in Mortar Specimens*. M.S. Thesis, University of Maryland, College Park, USA.
- Ceesay, J. (2007). *Characterization of Damage in Mortar and Concrete Specimens Due to Delayed Ettringite Formation (DEF)*. Ph.D. Thesis, University of Maryland, College Park, USA.

- Ceesay, J., Amde A. M., Azzam A., Livingston R., and Newman J. (2007). *Investigations of Modifications to the Duggan Test for Delayed Ettringite Formation*. Recent Advances in Concrete Technology, Eds: A.M. Amde, G. Sabnis and J.S.Y. Tan, Washington, DC, DEStech, 299-311.
- Chang, P.C, and Chi Liu, S. (2003). *Recent Research in Nondestructive Evaluation of Civil Infrastructures*. Journal of Materials in Civil Engineering, May/June pp. 298-304.
- Diamond, S. (1996). *Delayed Ettringite Formation-Processes and Problems*. Cement and Concrete Composites, Vol. 18, pp. 205-215.
- Diamond, S., and Ong, S. (1993). *Combined Effects of Alkali Silica Reaction and Secondary Ettringite Deposition in Steam Cured Mortars*. Cement Technology Symposium, American Ceramic Society PAC-Rim Conference, Honolulu, Ceramic Trans., in the press.
- Ekolu, S.O., Thomas, M.D.A., Hooton, R.D. (2006). *Implications of pre-formed microcracking in relation to the theories of DEF mechanisms*. Elsevier Ltd., Cement and Concrete Research 37 161-165.
- El-Korchi, T., Gress, D., Baldwin, K., and Bishop, P. (1989)., *Evaluating the Freeze-Thaw Durability of Portland Cement-Stabilized-Solidified Heavy Metal Waste Using Acoustic Measurements*. Environmental Aspects of Stabilization and Solidification of Hazardous and Radioactive Wastes. ASTM STP 1033, P.L. Cote and T. M. Gilliam, Eds., American Society for Testing Materials. Philadelphia, pp.184-191.
- Heinz, D., Ludwig, U., (1987). *Mechanism of Secondary Ettringite Formation in Mortars and Concretes Subjected to Heat Treatment*. American Concrete Inst. SP 100-105. Detroit, pp.2059-2071.
- Heinz, D., Ludwig, U., and Rudinger, I. (1989). *Delayed Ettringite Formation in Heat-Treated Mortars and Concretes*. Concrete Precasting Plant and Technology, Vol. 11, pp. 56-61.
- Janssen, D.J., and Snyder, M.B. (1994). *Resistance of Concrete to Freezing and Thawing*. Strategic Highway Research Program, Washington, D.C. June.
- Krautkramer, J. and Krautkramer, H., (1990). *Ultrasonic Testing of Materials*, 4th Ed., Springer-Verlag, New York.
- Lawrence, C.D. (1993). *Laboratory Studies of Concrete Expansion Arising from Delayed Ettringite Formation*. Publication c/16, British Cement Association. Crowthorne, Berks, UK, 147 pp.

- Lin, J.M. and Sansalone, M.J., (1996). *Impact-Echo Studies of Interfacial Bond Quality in concrete: Part I—Effects of Unbonded Fraction of Area*. ACI Materials Journal, Vol. 93, No. 3, May-June, pp. 223-232.
- Livingston, R., Sutin, A., Ceary, M., McMorris, N., and Amde, A.M. (2005). *Characterization of Distributed Damage in Concrete Using Advanced Impact-Echo Method*. The Eleventh International Conference on Fracture, Turin, Italy, Section 15, March 2005, Paper 4548.
- Malhotra, V. M., & Carino N. J., (Eds.). (1991). *Handbook on Nondestructive Testing of Concrete*. Boca Raton, Florida: CRC Press, Inc.
- McMorris, N., Amde, A. M., Ceesay, J., Ramadan, J., and Livingston, R. A. (2007) *Improved Impact-Echo Method for Quantification of Distributed Damage in Concrete*. Recent Advances in Concrete Technology, Eds: A.M. Amde, G. Sabnis and J.S.Y. Tan, Washington DC, 185-194.
- Mielenz, R.C., Marusin, S.L., Hime, W.G., and Jugovic, Z.T. (1995). *Investigation of Prestressed Concrete Railway Tie Distress*. Concrete International, Dec., pp 62-68.
- Ramadan, E.O. (2000). *Experimental and Theoretical Study of Delayed Ettringite Damage in Concrete*. Ph.D. Thesis, University of Maryland, College Park, USA.
- Sansalone, M., and Carino, N. J., (1986). *Impact-Echo: A Method for Flaw Detection in Concrete Using Transient Stress Waves*. NBSIR 86-3452, National Bureau of Standards. Sept, p.222.
- Sansalone, M. and Carino, N.J., (1991). *Stress Wave Propagation Methods*, in *Handbook on Nondestructive Testing of Concrete*, Ed. V. M. Malhotra and N.J. Carino, CRC Press, Boca Raton, FL, pp. 275-304.
- Sansalone, M., and Carino, N.J., (1988a). *Impact-Echo Method: Detecting Honeycombing, the Depth of Surface-Opening Cracks, and UngROUTED DUCTS*. Concrete International, Vol. 10, No. 4, April, pp.38-46.
- Sansalone, M., and Carino, N.J., (1988b). *Laboratory and Field Study of the Impact-Echo Method for Flaw Detection in Concrete in Nondestructive Testing of Concrete*. Ed. H.S. Lew, ACI SP-112, American Concrete Institute, pp. 1-20.
- Sansalone, M. and Streett, W. B., (1997). *Impact-Echo: Nondestructive Testing of Concrete and Masonry*. Bullbrier Press, Jersey Shore, PA.
- Sutin, N.M., and Jaafar, M.S. (2003). *Evaluating Efficiency of Nondestructive Detection of Flaws in Concrete*. Russian Journal of Nondestructive Testing, Vol. 39, No. 2, pp. 87-93. Translated from Defektoskopiya, No.2, 2003 pp.3-10.

Thomson, W.T. (1981). *Theory of Vibration with Applications*. 2th Ed. Prentice-Hall, Inc., Englewood Cliffs, N. J.

Yehia, S., Abudayyeh, O., Nabulsi, S., and Abdelqader I. (2007). *Detection of Common Defects in Concrete Bridge Decks Using Nondestructive Evaluation Techniques*. Journal of Bridge Engineering, March/April pp. 215-225.